Neutrino Physics

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Outline (today's lecture)

1. History of neutrinos
2. The discovery of neutrino oscillations
3. The current landscape of neutrino oscillation experiments
4. Our knowledge of neutrino mixing
5. Open questions in neutrino physics

I will be biased towards neutrino oscillation physics. But there is a lot more neutrino physics. We can discuss about it anytime!

Outline (tomorrow’s lecture)

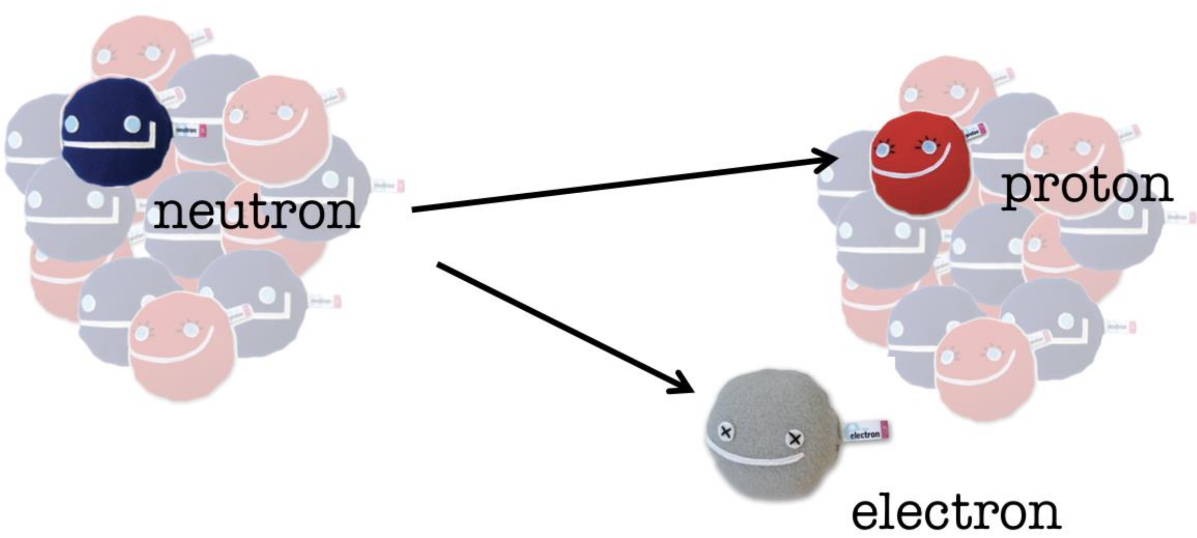
1. Neutrino “anomalies”
2. The search for sterile neutrinos
3. The Short Baseline Program at Fermilab
4. CP violation in the neutrino sector
5. Prospects for future long baseline searches

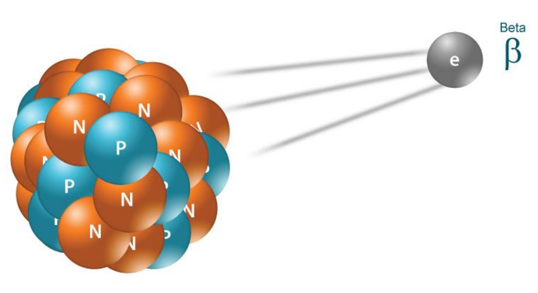
In this case, I will be biased towards the neutrino program at Fermilab. There is a lot going on and it’s a very exciting time!

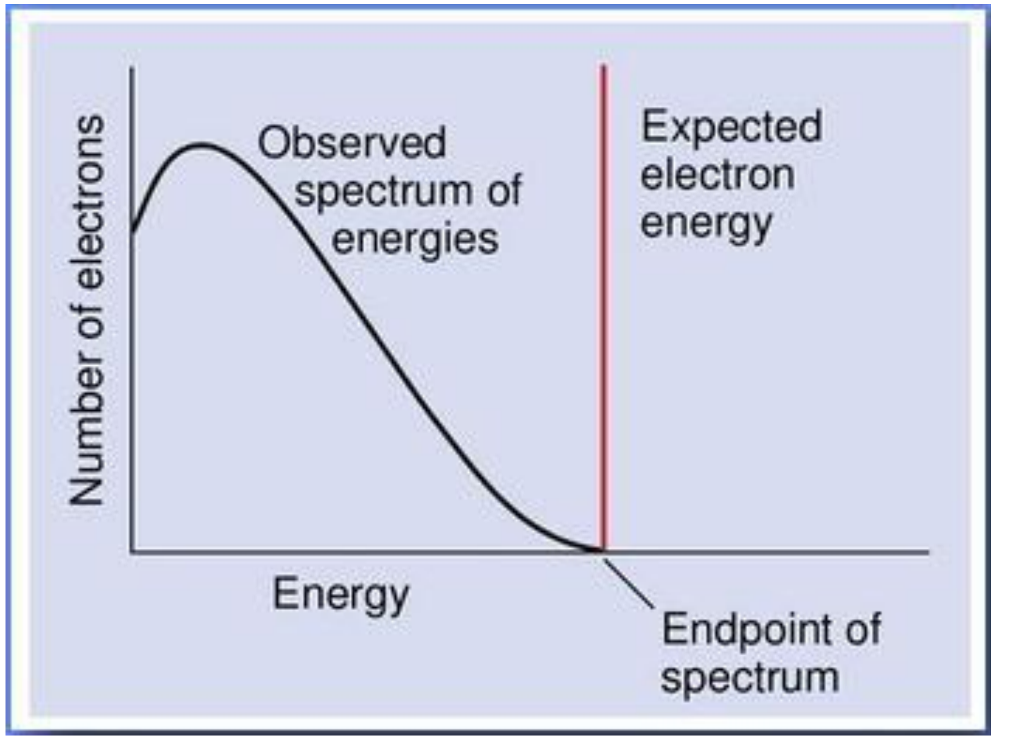
Disclaimer

- There are a lot of very good neutrino physics theory, experiments, results which I won’t describe/detail
- I am sorry if I won’t describe your favorite neutrino experiment, but I needed to make choices!

Beta decay before 1930

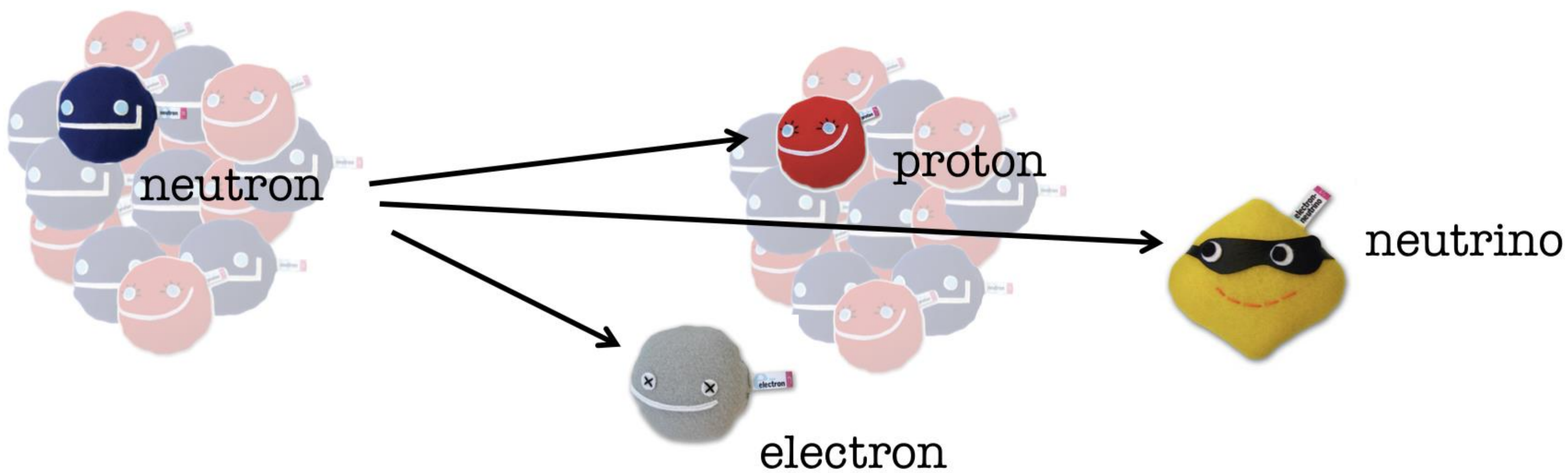


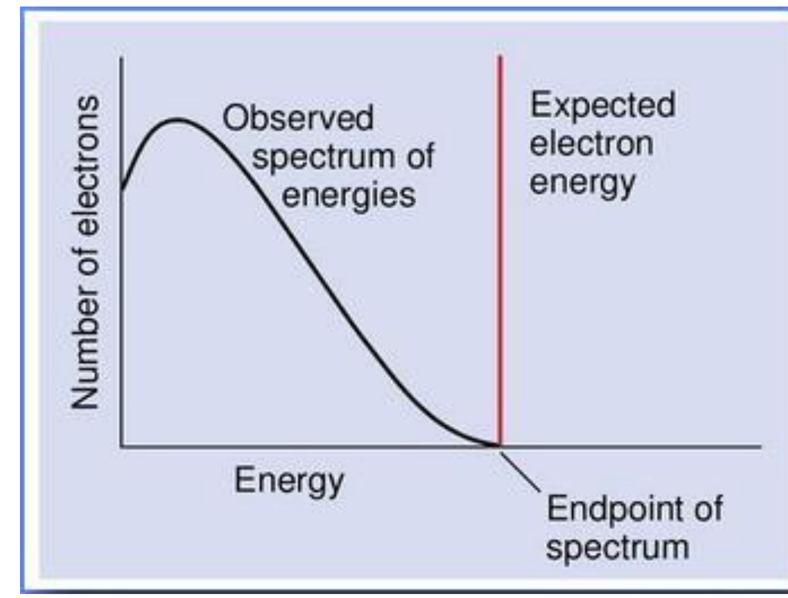




- "Beta rays" were observed as a consequence of radioactive decays
- Chadwick et al measured their spectrum and reported a **continuous** distribution instead of an **expected monochromatic line**
- Does this mean that **energy conservation is violated** in this process?

Pauli’s desperate remedy to save energy conservation





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Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und

In 1930, Pauli hypothesizes that in the beta decay, a kind of a “neutron” is also emitted

Pauli's desperate remedy to save energy conservation

Dear Radioactive Ladies and Gentlemen,
as the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant . W. Pauli, December 1930

- December 1930, Pauli sends a letter to the physicists attending a conference in Tubingen
- Pauli is ashamed to introduce **a particle "we will never be able to detect"**, to save energy conservation (!)

Attempts for neutrino discovery

- In 1951, Reines and Cowan built a prototype for anti-neutrino detection called **“El Monstro”**

GIANT LIQUID SCINTILLATION DETECTORS AND THEIR APPLICATIONS*

FREDERICK REINES

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

I. GENERAL CONSIDERATIONS LEADING TO THE DEVELOPMENT OF LARGE DETECTORS

WHEN Clyde Cowan and I started in 1951 to pursue the free neutrino,[1] we knew that an essential ingredient in any successful scheme would be a solid or liquid target consisting largely of protons and measuring approximately a cubic meter. Furthermore, the events which occurred in this target had to

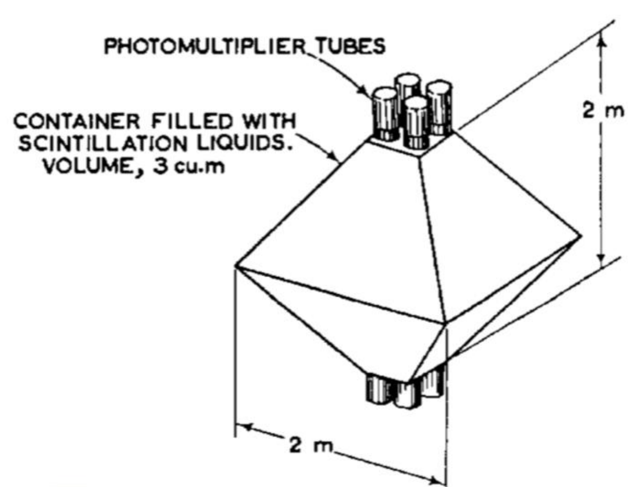


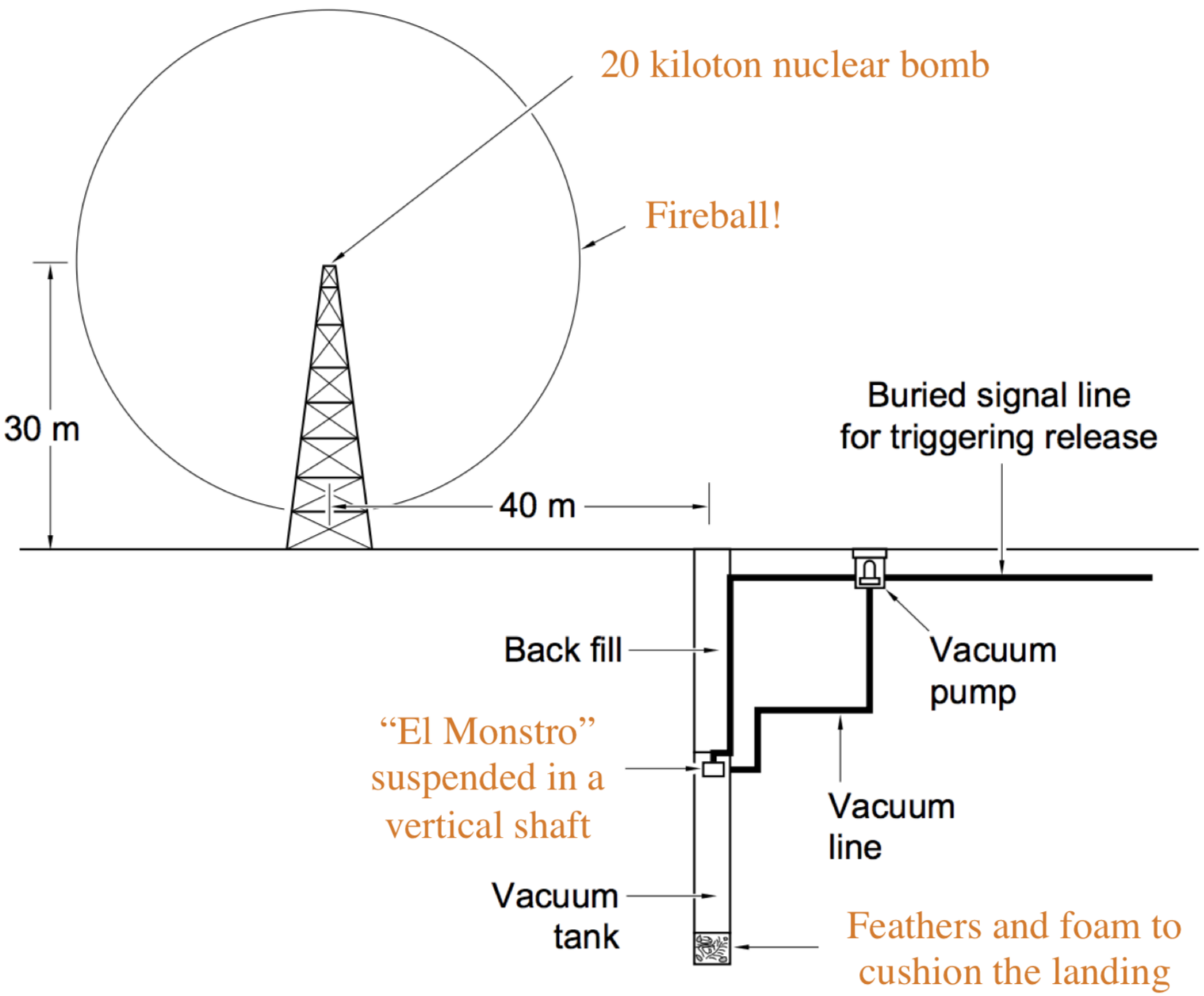
Fig. 1. Sketch of ‘El Monstro’, first Los Alamos attempt at a giant liquid scintillation detector (1952).

- The idea was to look for Inverse Beta Decay in liquid scintillator:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

- This process has a clear signature, given the time coincidence between the prompt (e^+) and delayed (n capture) energy depositions

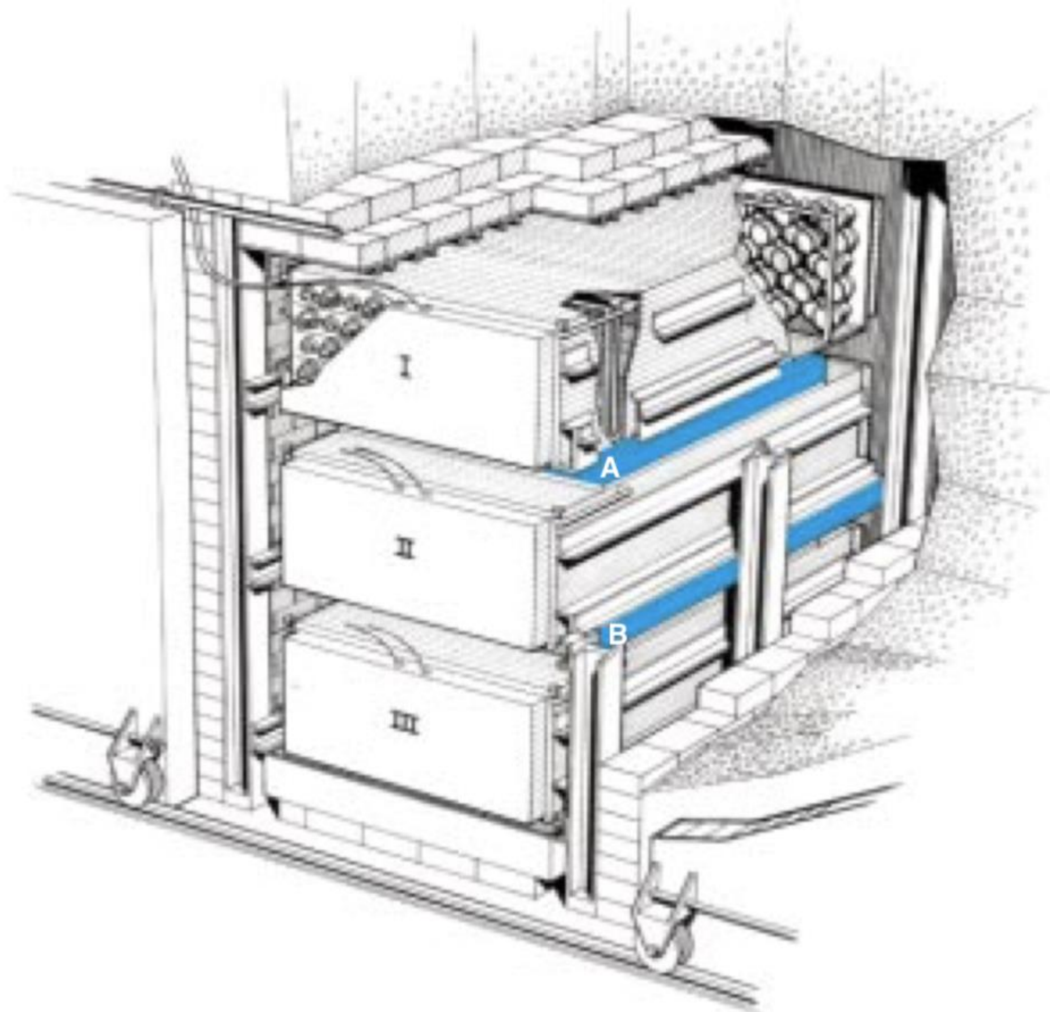
El Monstro approved at Los Alamos National Lab



Los Alamos Science, Number 25 (1997)

- Neutrinos interact only *weakly*, so a powerful source is needed
- Why not a **nuclear bomb**? El Monstro would be left free falling during the explosion, and recovered some days later….
- **This was approved** by LANL's director…
- …but it never happened!

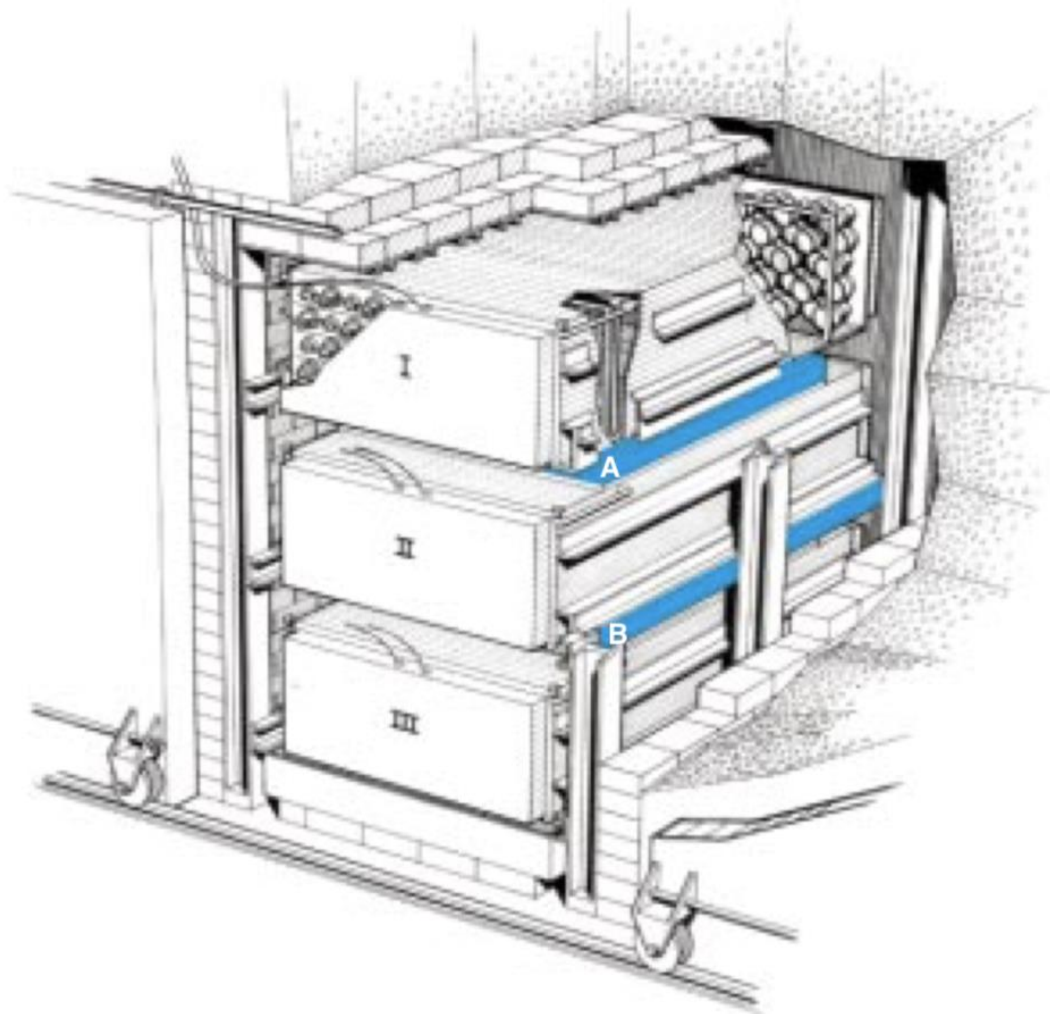
The Savannah River Neutrino Experiment (1956)

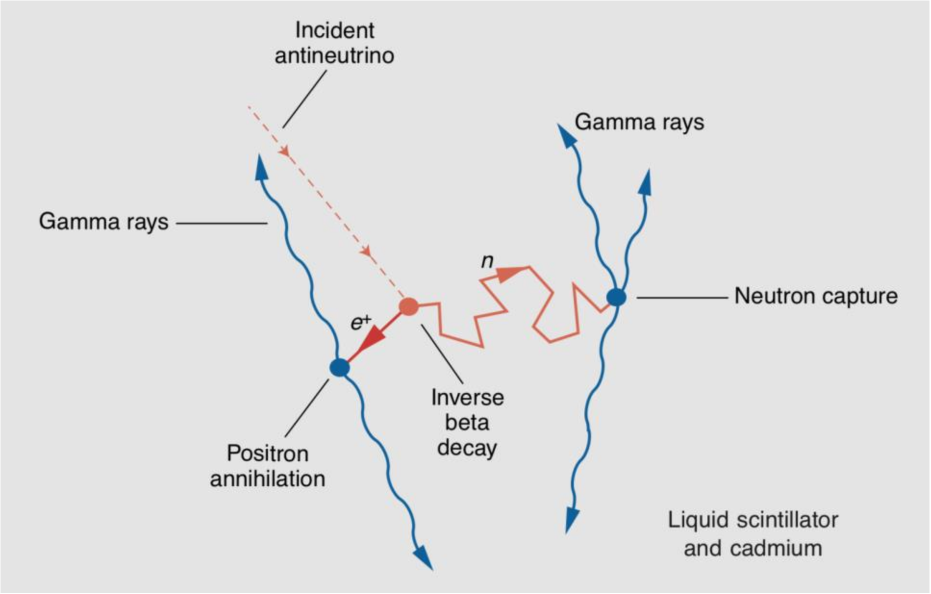


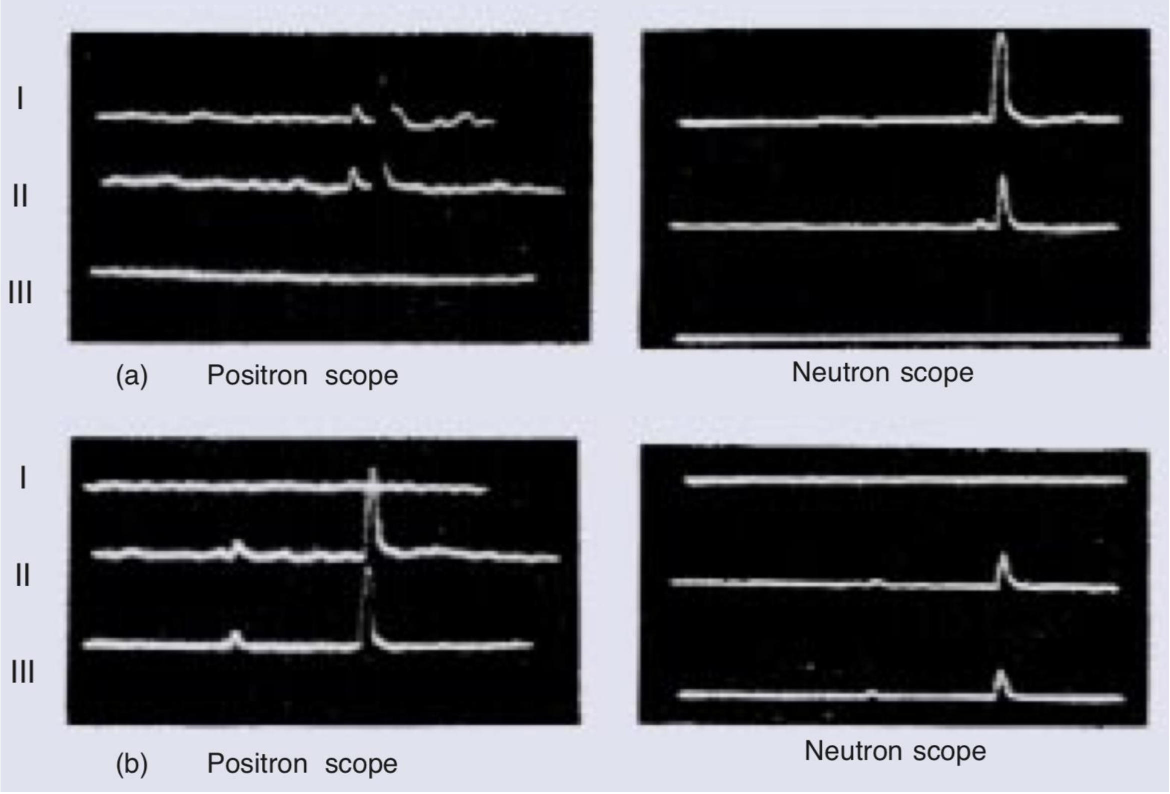
$$n + {}^{113}_{48}Cd \rightarrow {}^{114}_{48}Cd + \gamma$$

- **Placed close to the fission reactor** of Savannah River in South Carolina (11m from the core)
- 12m concrete overburden from cosmic rays and a smart coincidence mechanism to suppress backgrounds
- A and B are water targets for the inverse beta decay doped with Cd
- The tanks I, II, and III contain the liquid scintillator

The Savannah River Neutrino Experiment (1956)







$$n + {}^{113}_{48}Cd \rightarrow {}^{114}_{48}Cd + \gamma$$

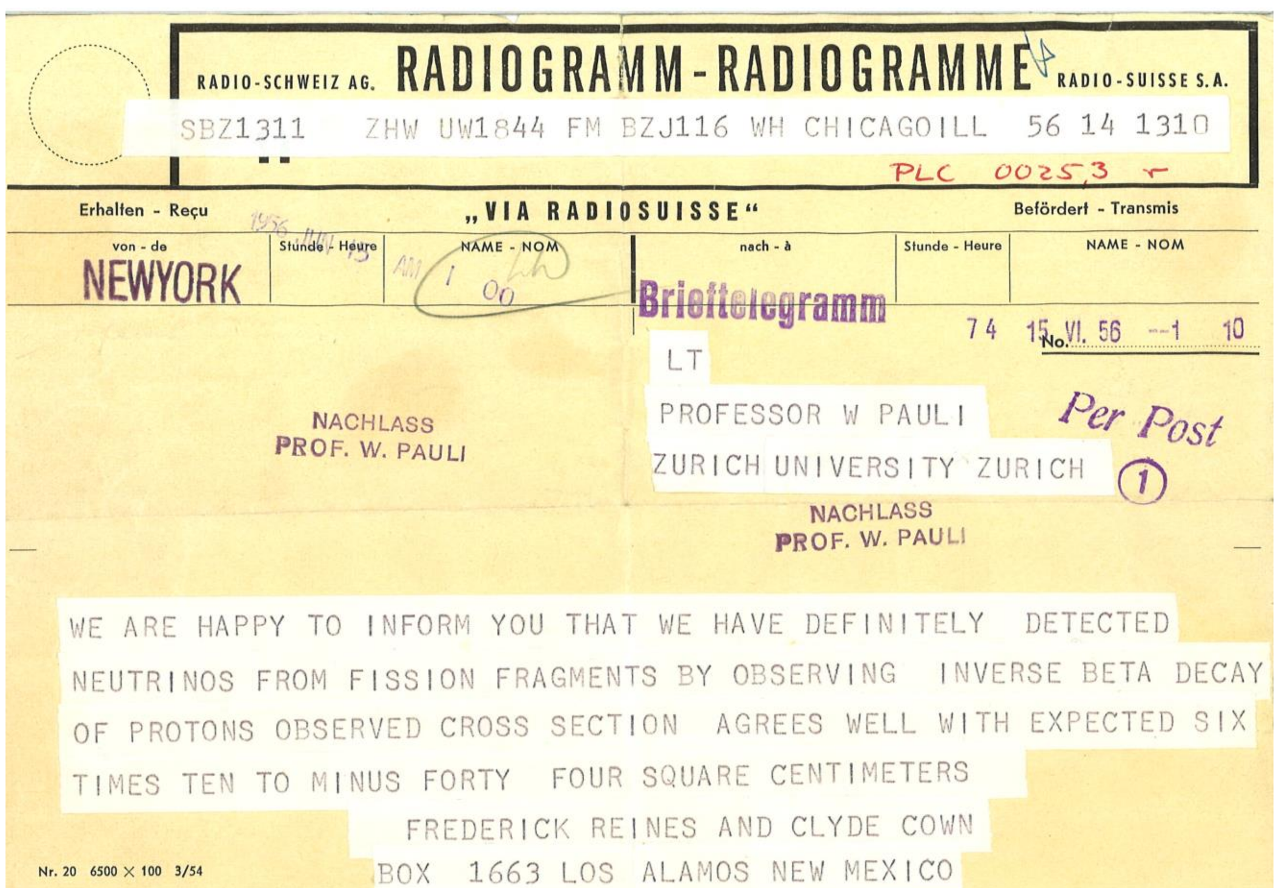
The neutron signal is delayed by 3-10 μs

The electron antineutrino discovery (1956)

Clyde Cowan

Fred Reines

1995



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

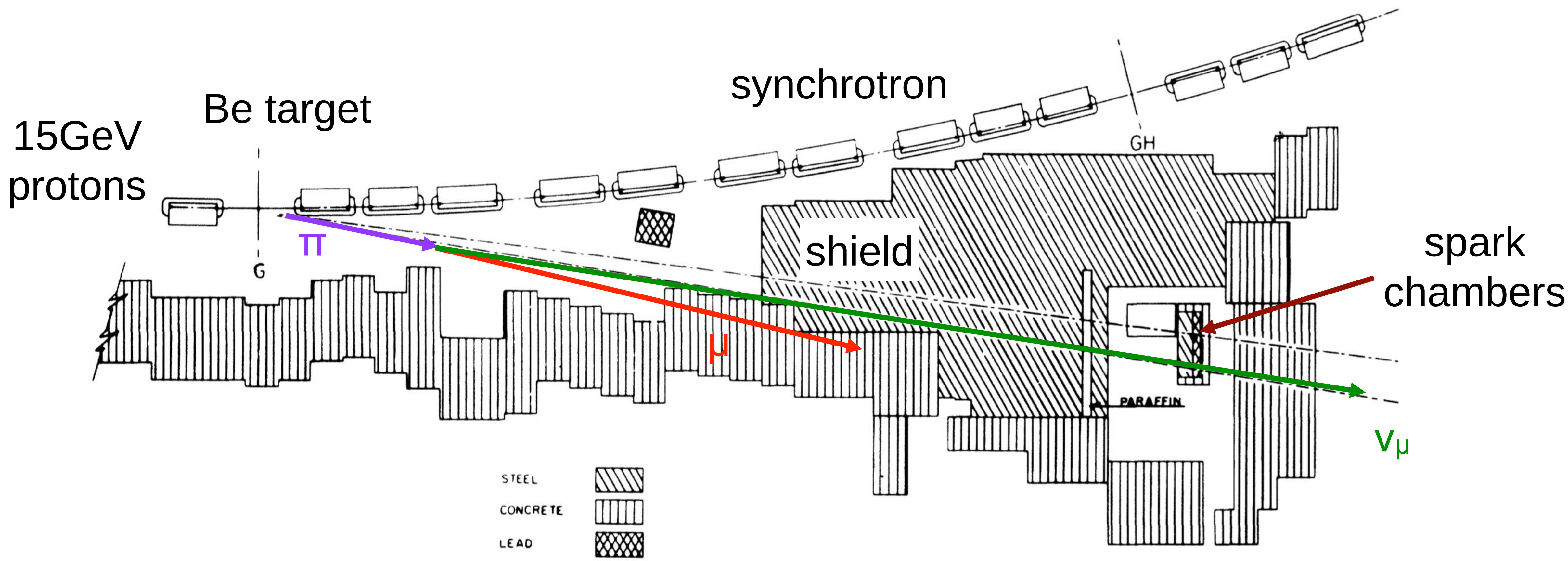
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

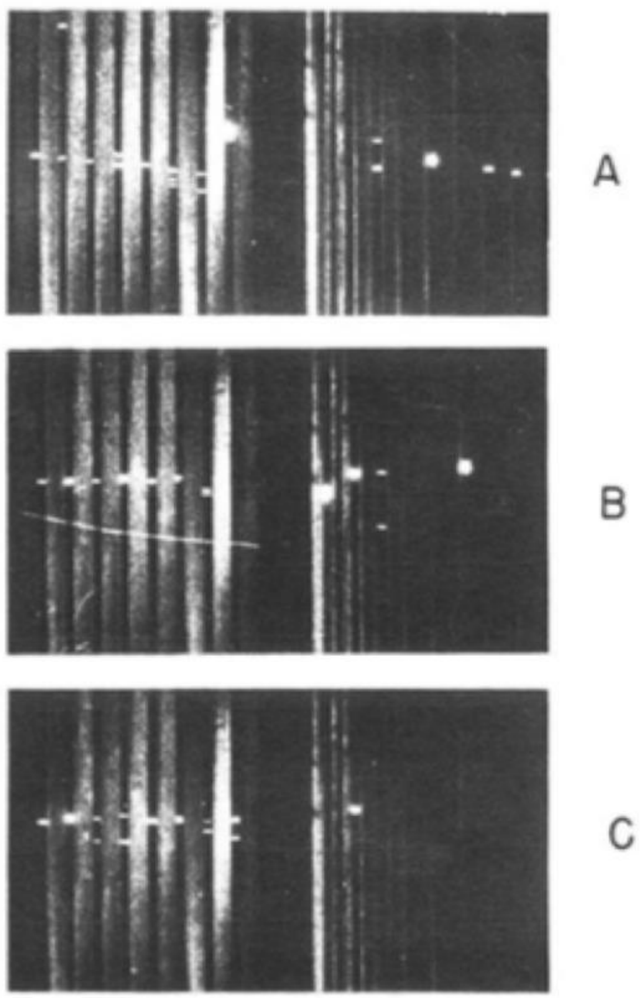
Evidence for other types of neutrino?

- First accelerator based neutrino experiment!
- Alternating Gradient Synchrotron (AGS) @ Brookhaven
- $\rho = R(\mu \rightarrow e + \gamma)/R(\mu \rightarrow e + \nu + \bar{\nu})$ ~10^{-4} (theo) vs <10^{-8} (exp)

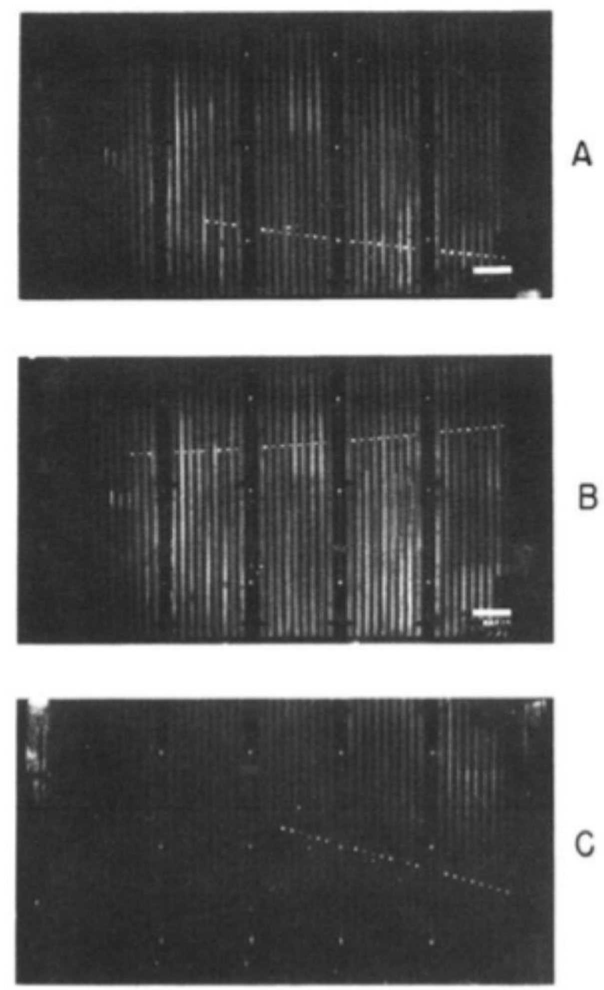


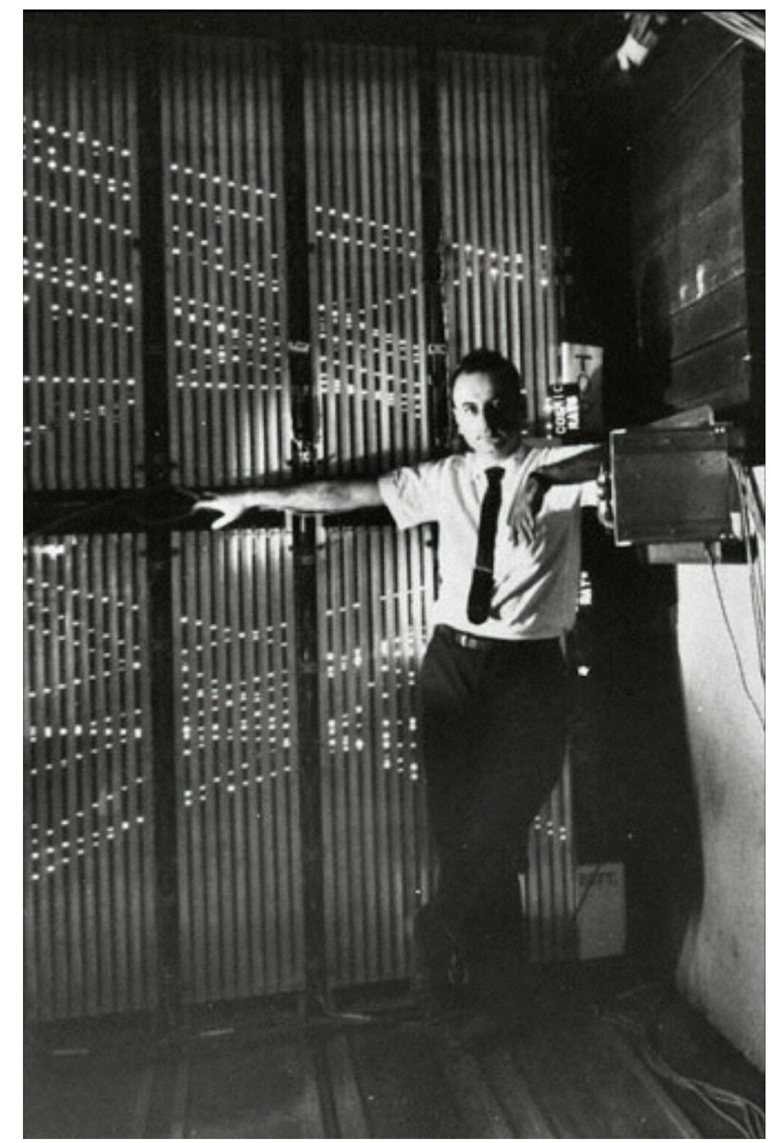
The discovery of muon neutrino (1962)

Electron showers



Muon tracks



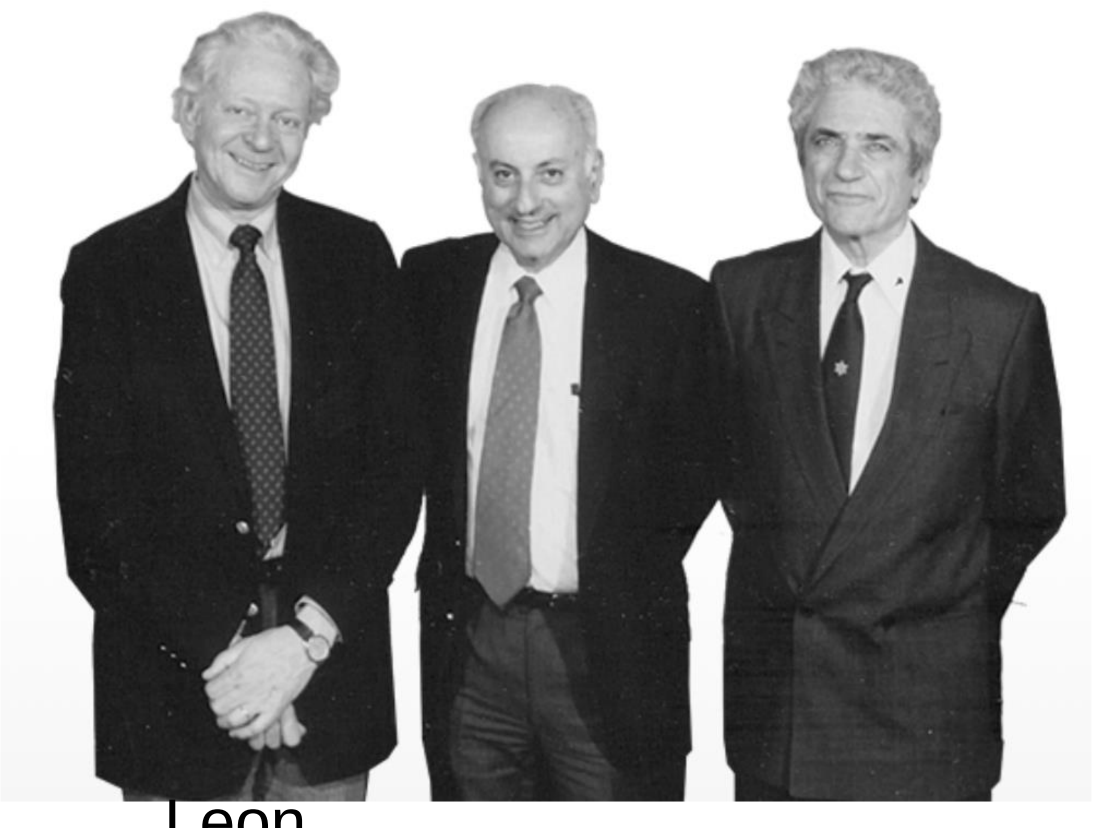


Melvin Schwartz standing
next to spark chamber

- Data taken with pictures and analyzed by hand!

The discovery of muon neutrino (1962)

- Leon Lederman, Melvin Schwartz, and Jack Steinberger found **34 single muon tracks** originating inside the detector and **only 6 electron showers**
- This proves that neutrinos from muon decay and beta decay are different.

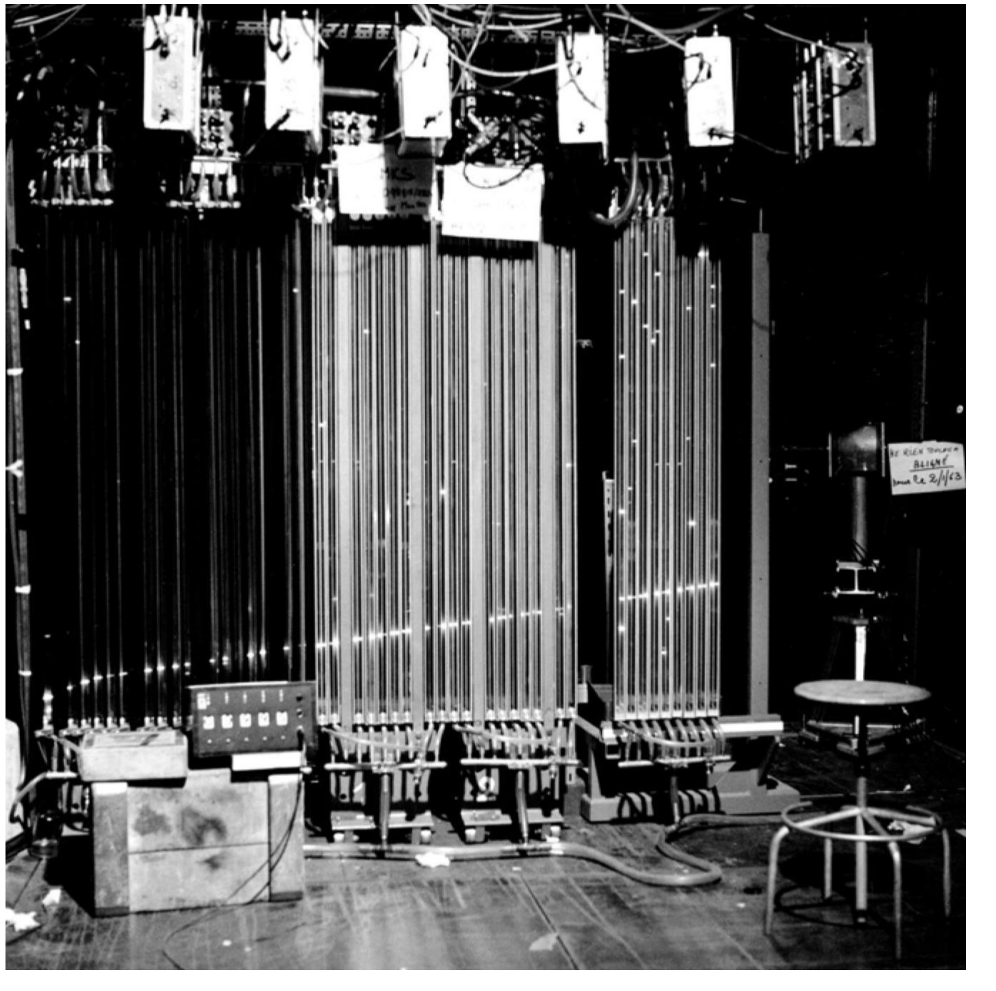


Leon Lederma n

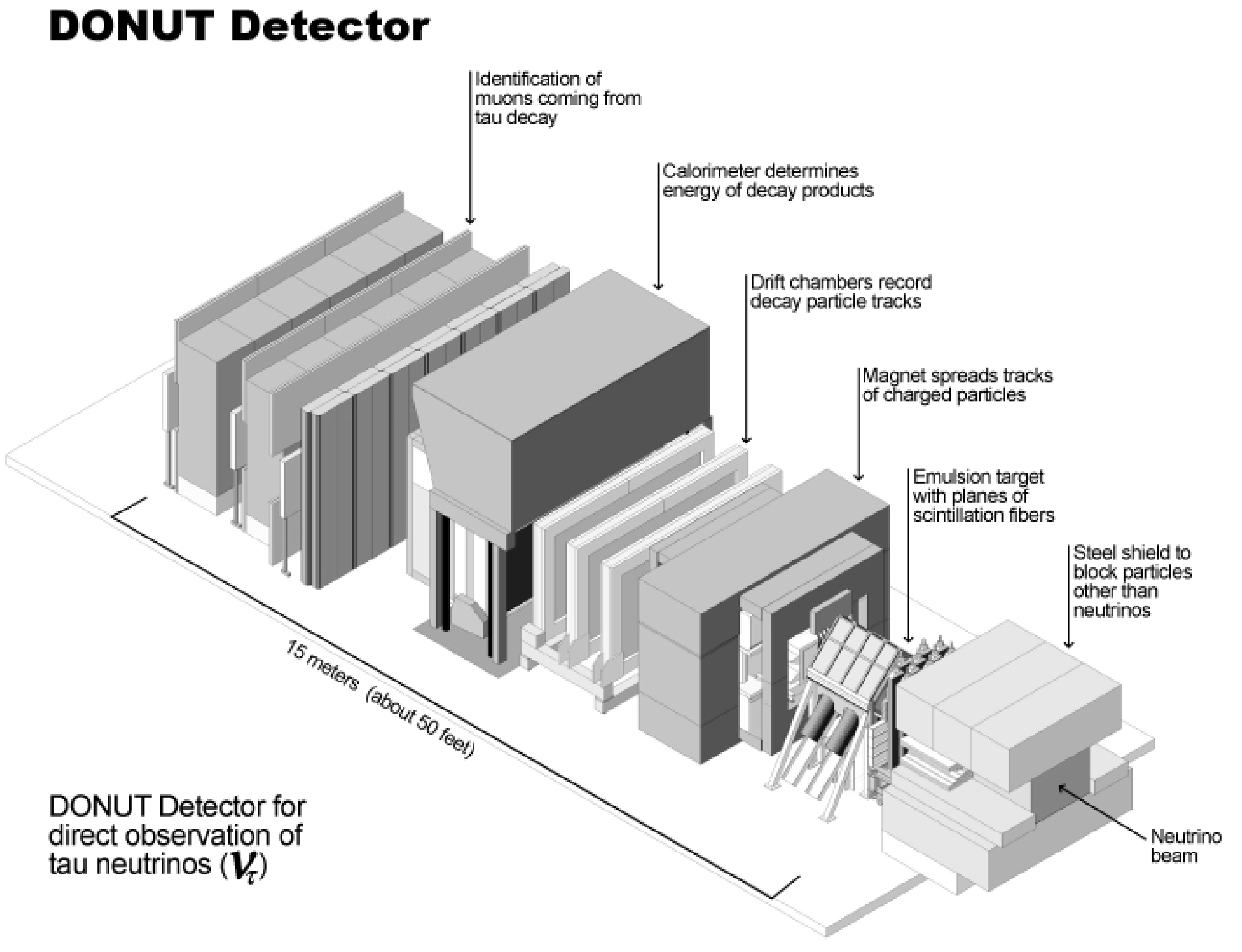
Mel Schwartz

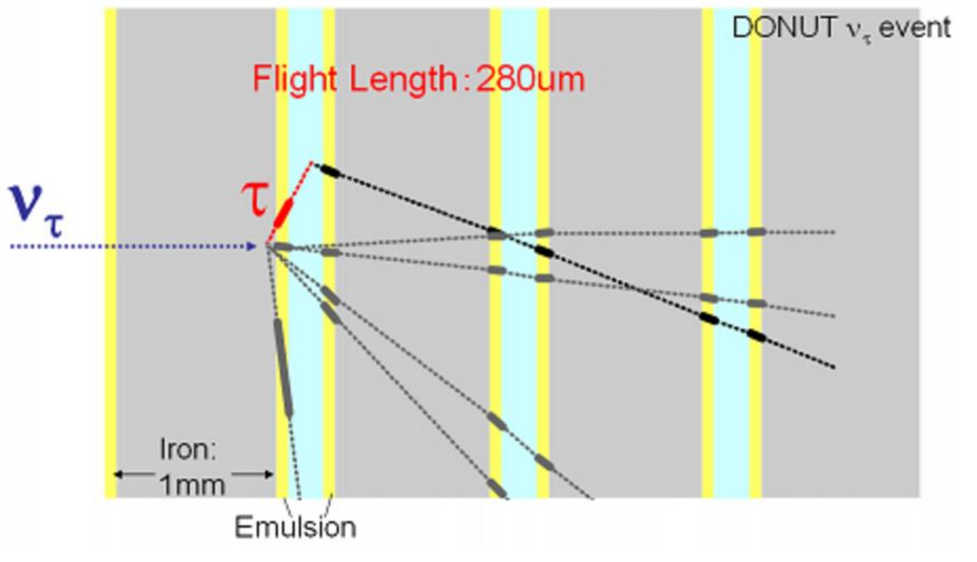
Jack Steinberger

1988



The DONUT experiment: discovery of ν_τ

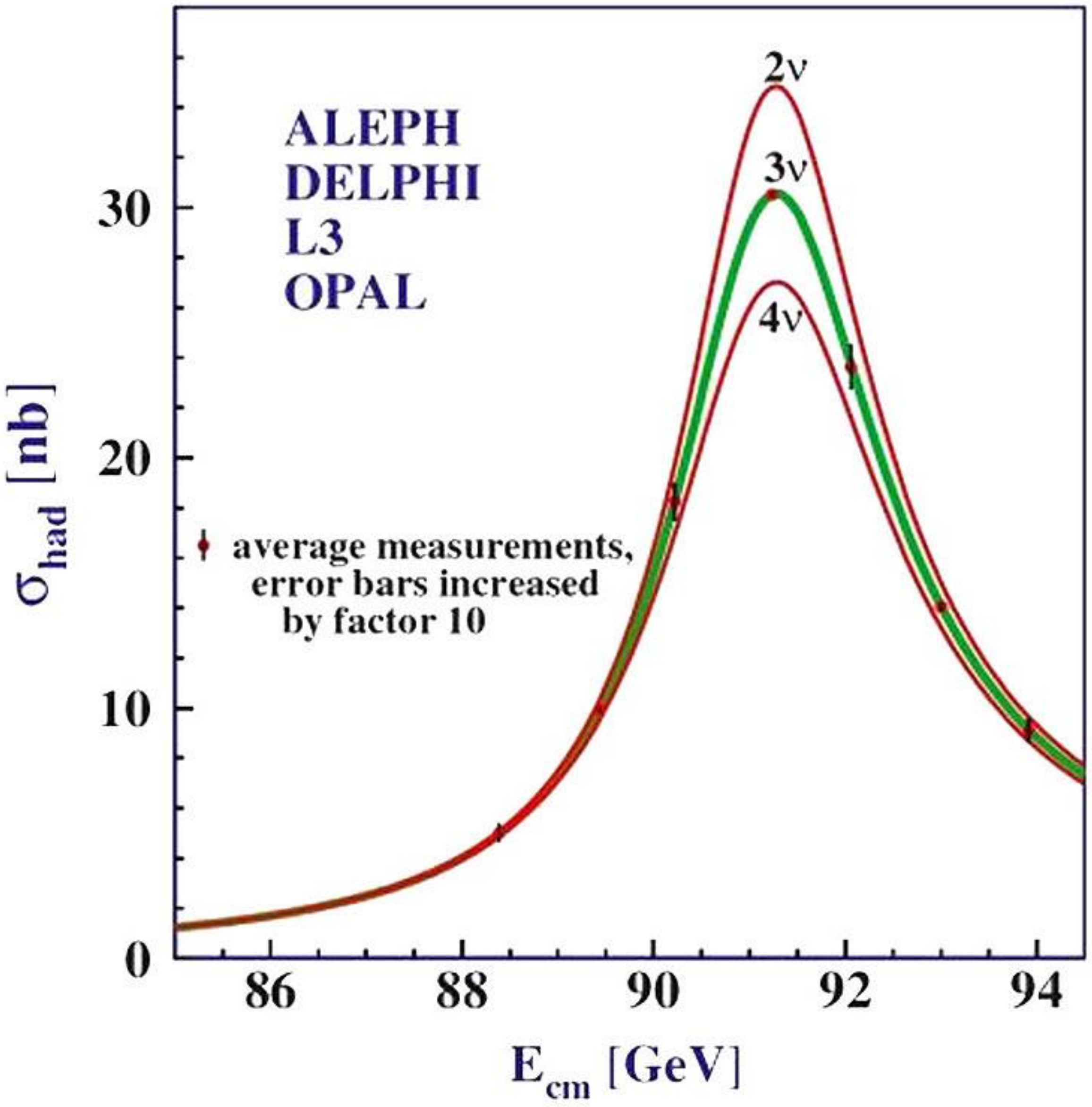




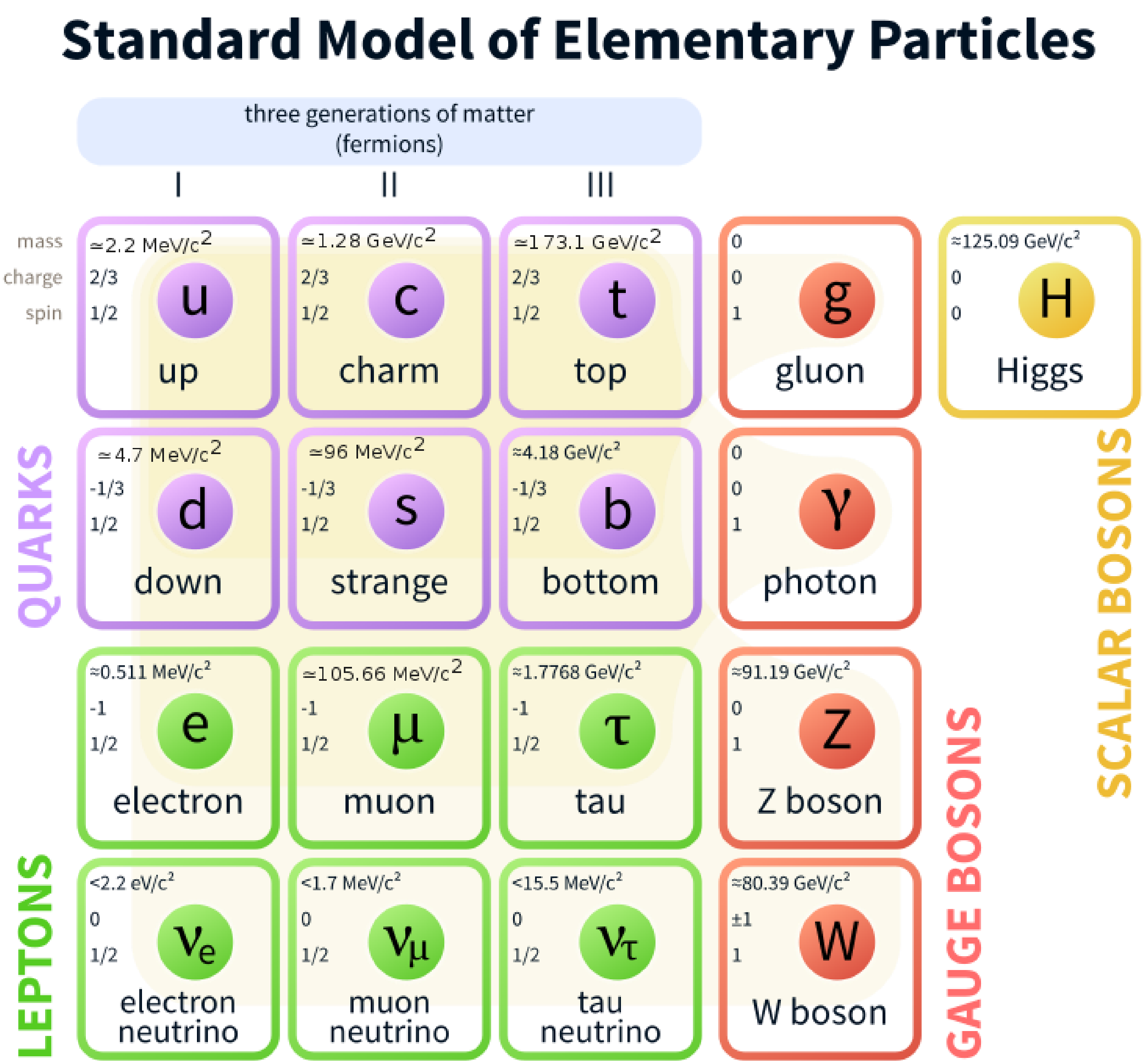
- After the discovery of the τ in the 70's, the hunt for ν_τ started!
- DONUT operated at Fermilab in 1997 using the Tevatron
- proton beam
- The τ is heavy (~1.7 GeV) so its production requires the decay of charmed mesons
- In 2000, **4 candidate events** identified with a 0.2 background expectation

How many neutrinos?

Precision measurements of the Z width at LEP showed that there are **3 lepton families (and thus 3 weakly interacting neutrinos)**



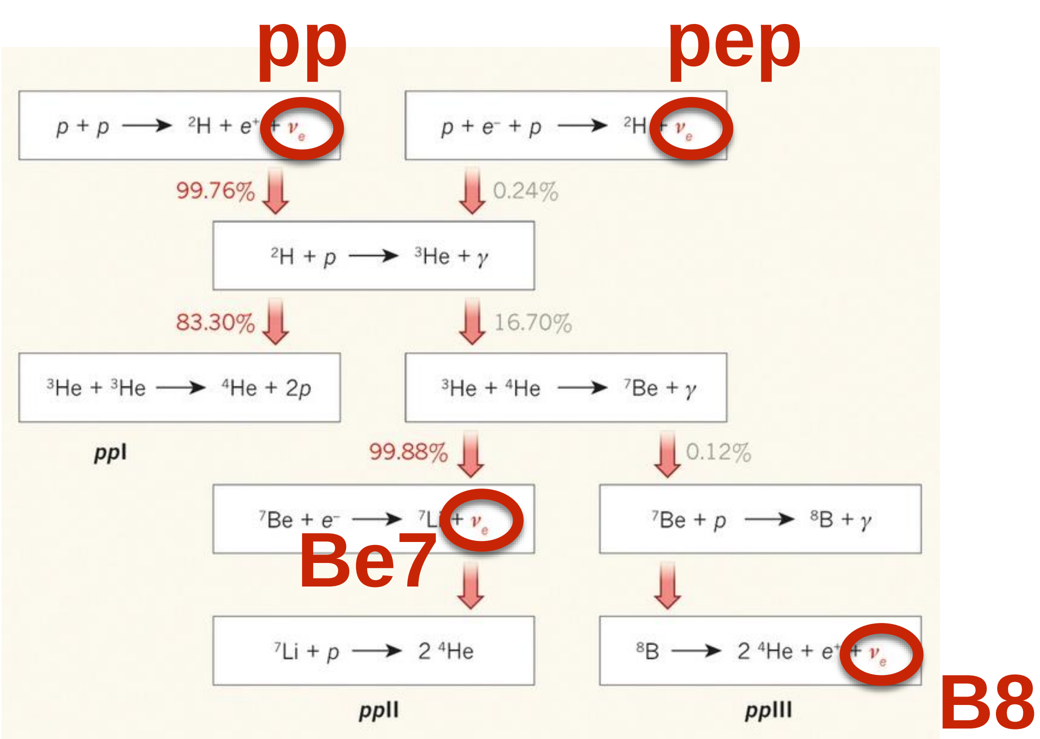
The Standard Model picture

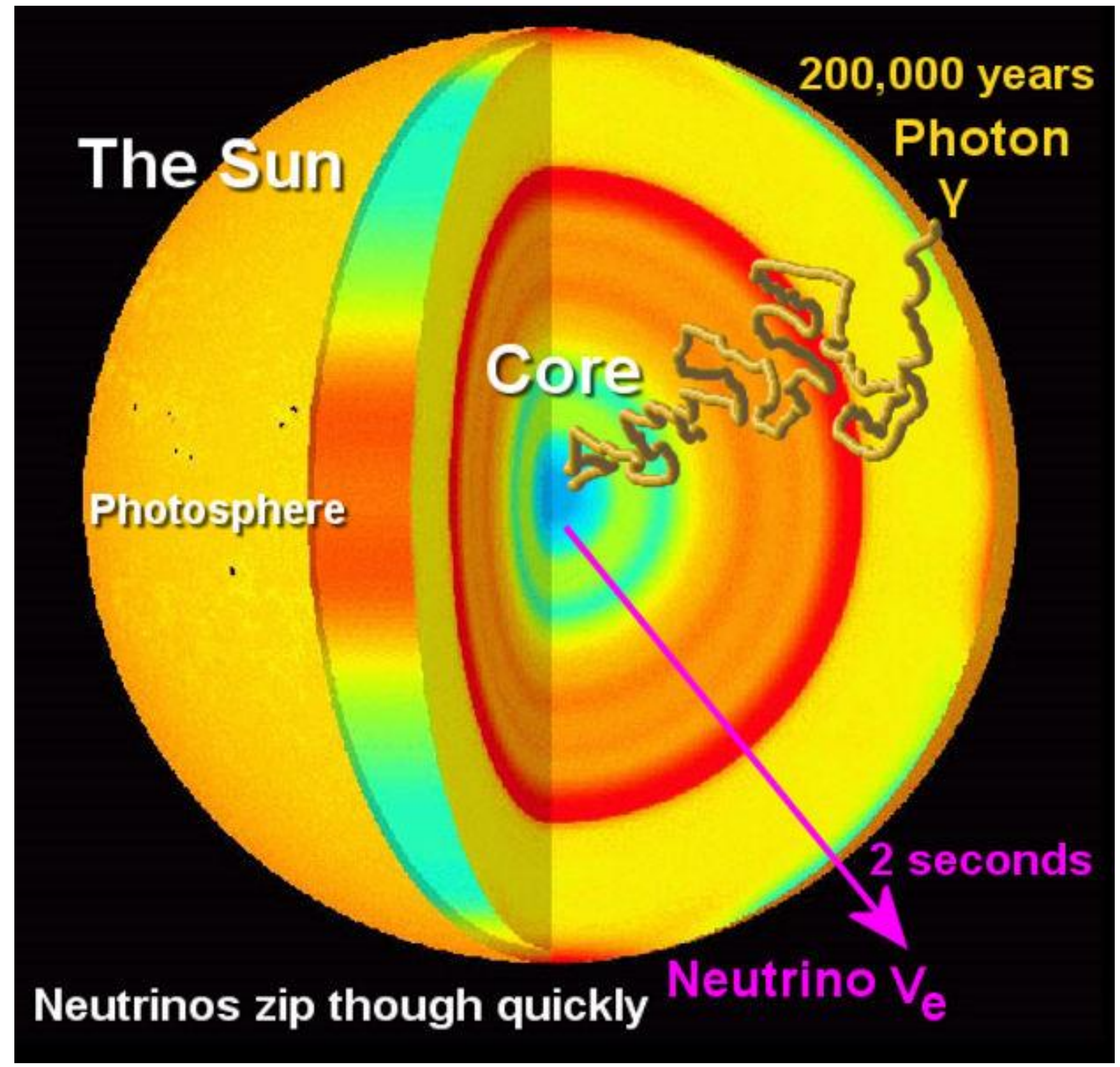


- Dynamical definition of neutrinos:
  1. **ν_e**'s are produced in weak interactions associated to **electrons**
  2. **ν_μ**'s are produced in weak interactions associated to **muons**
  3. **ν_τ**'s are produced in weak interactions associated to **taus**
- **Is that it?**

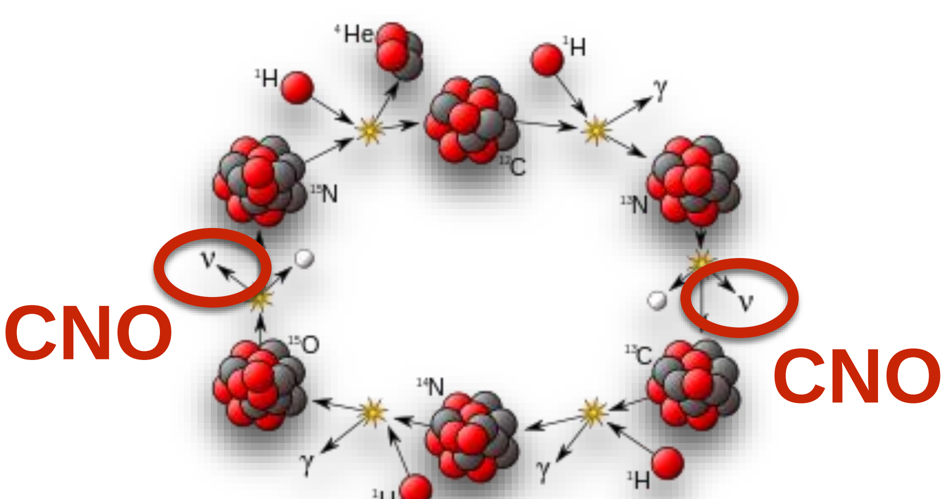
Solar neutrinos

pp chain (99%)



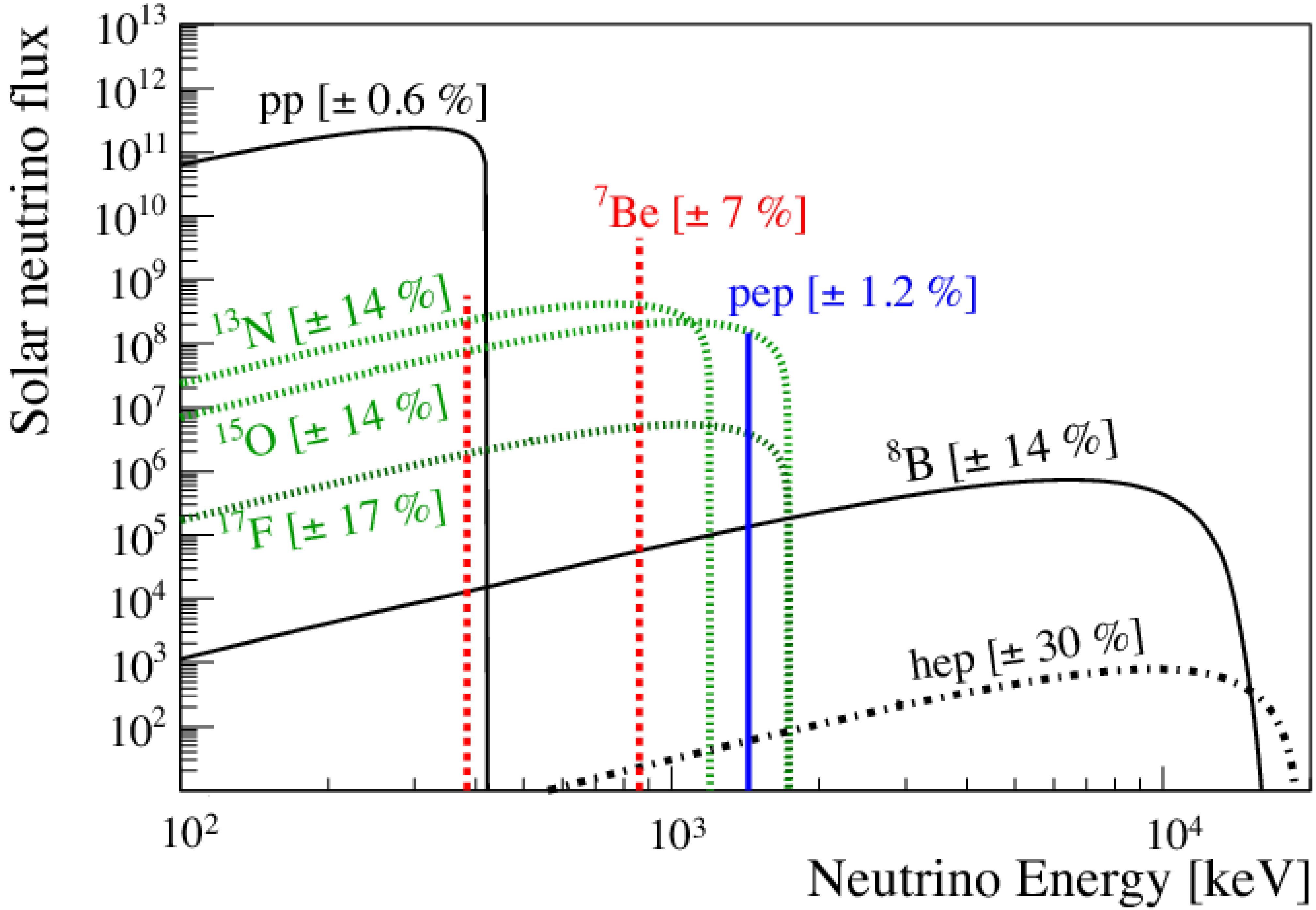


CNO cycle (minor contribution)



The Sun is powered by nuclear fusion reactions. 4p become a α nucleus releasing ~26MeV

Solar neutrino spectrum

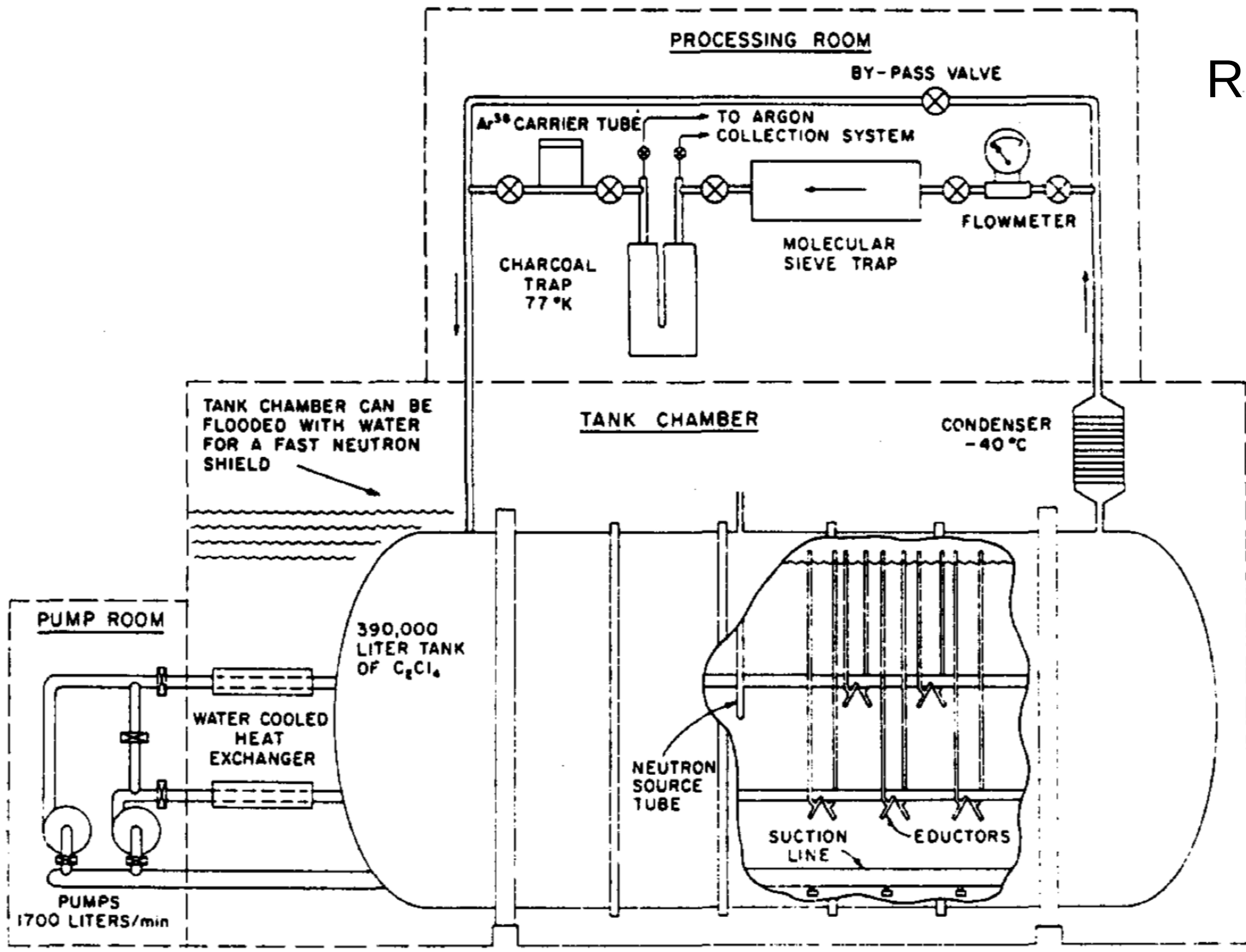


The Homestake experiment

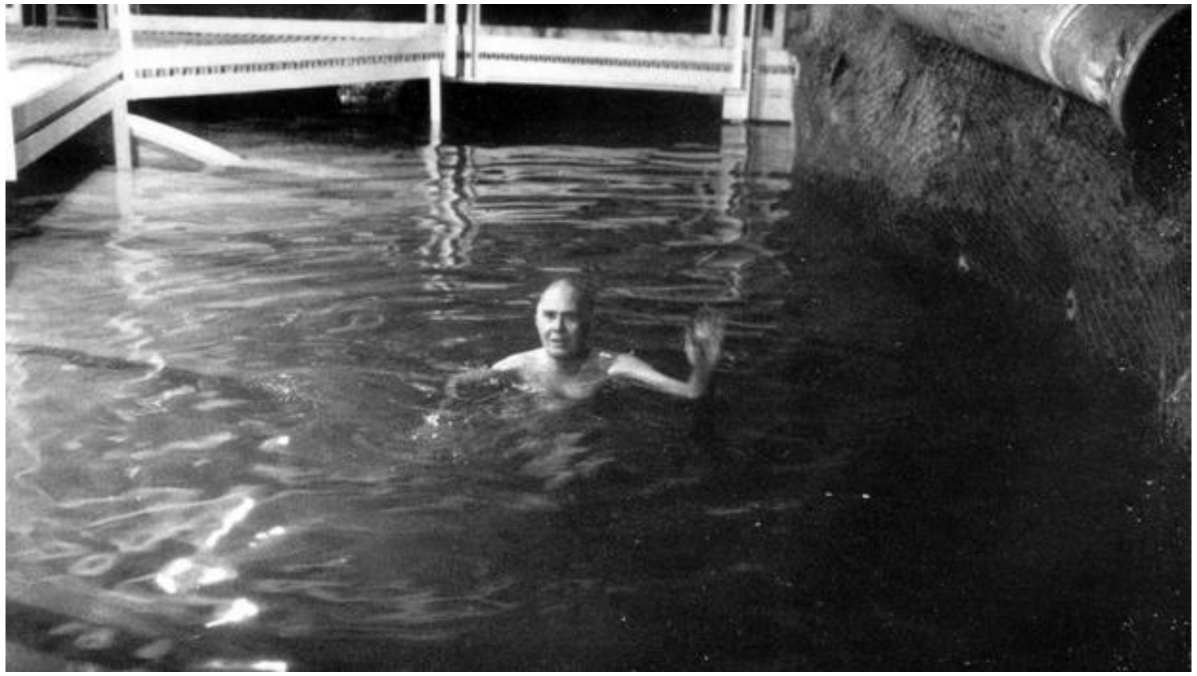
- At the end of the 60's, **John Bahcall had a solid theory for describing the Sun**, and **Ray Davis** decided to test it by **measuring directly solar neutrinos**
- 615 tons of C_2Cl_4 (perchloroethylene)
- Expected ~8 captures per day in the whole volume (threshold 814keV)
- ^{37}Ar decays with $T_{1/2}$ of 35 days

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

The Homestake experiment

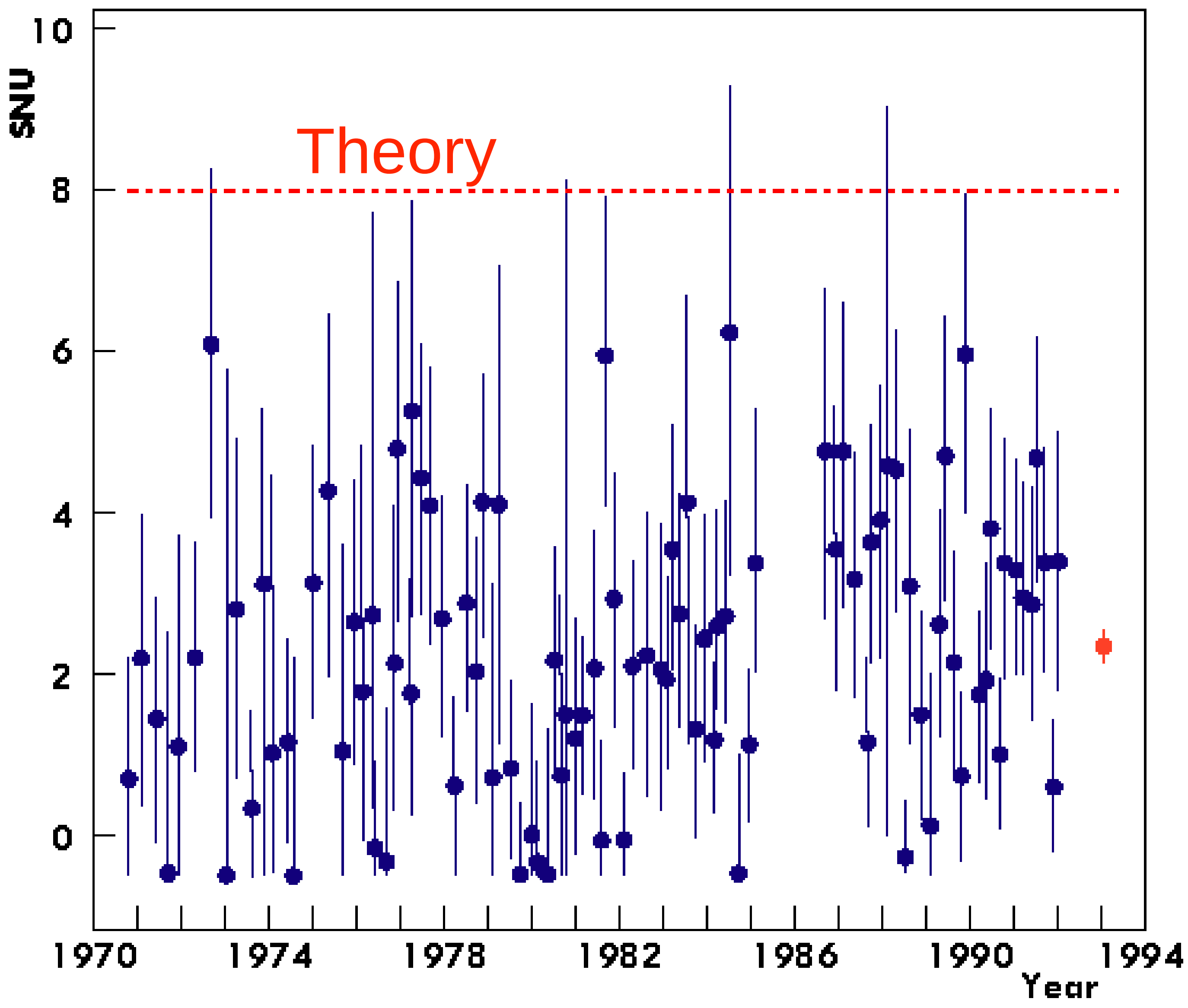


Reference: [R. Davis review of the Homestake experiment]



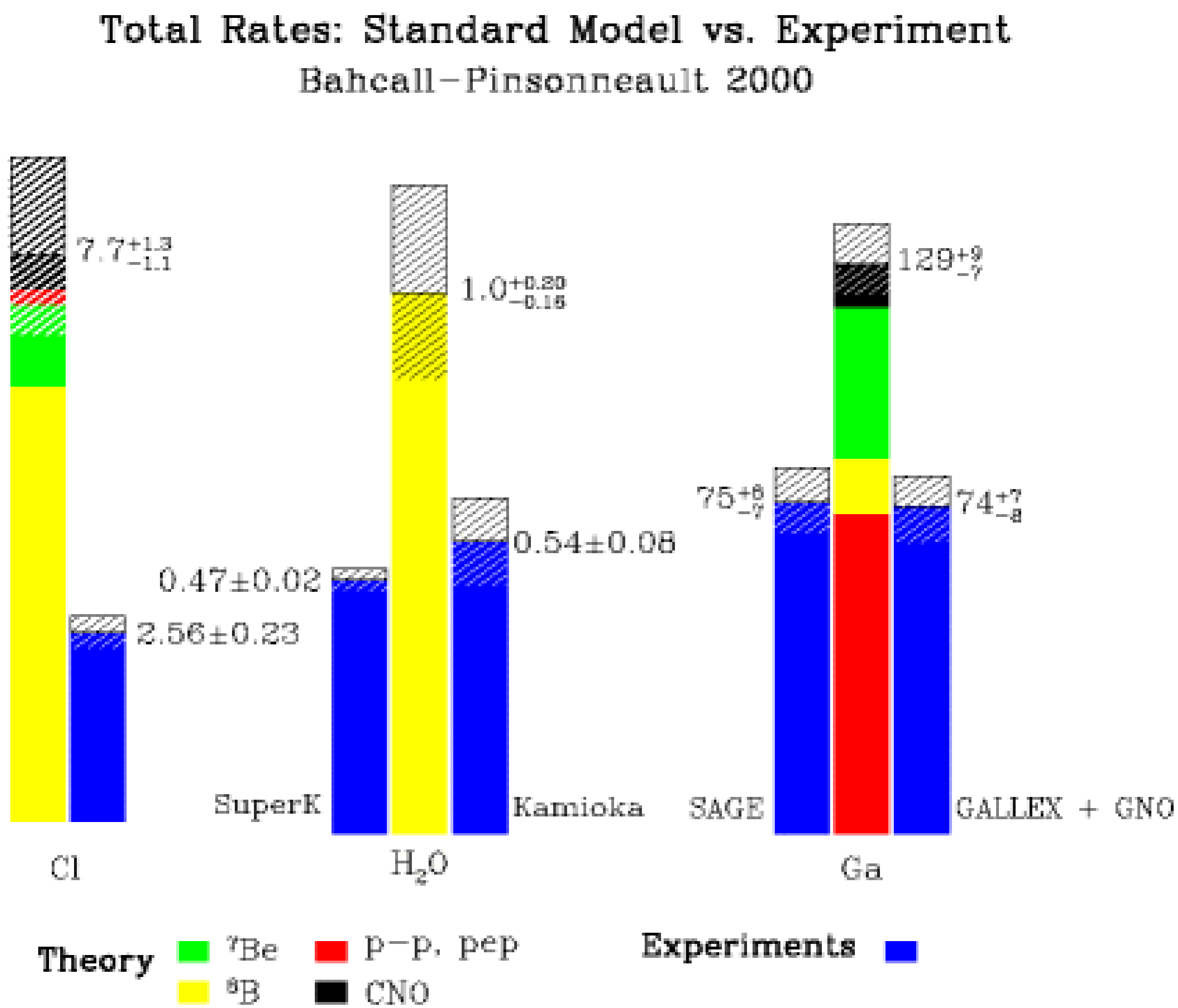
- The experiment was located 1480m underground in the Homestake Gold Mine at Lead, South Dakota
- There is a complex system to recover just a few atoms of ^{37}Ar in tons of C_2Cl_4
- ^{37}Ar decays by EC and emission of ~2.8keV Auger electrons from the K shell
- ^{37}Ar decays identified in miniature proportional counters filled with Ar and ~7% of CH_4

Results from the Chlorine experiment



- 1SNU = 10^{-36} captures per second per ^{37}Cl atom
- Is John Bahcall wrong?
- Are Ray Davis and his experiment wrong?
- **Why are we missing neutrinos?**

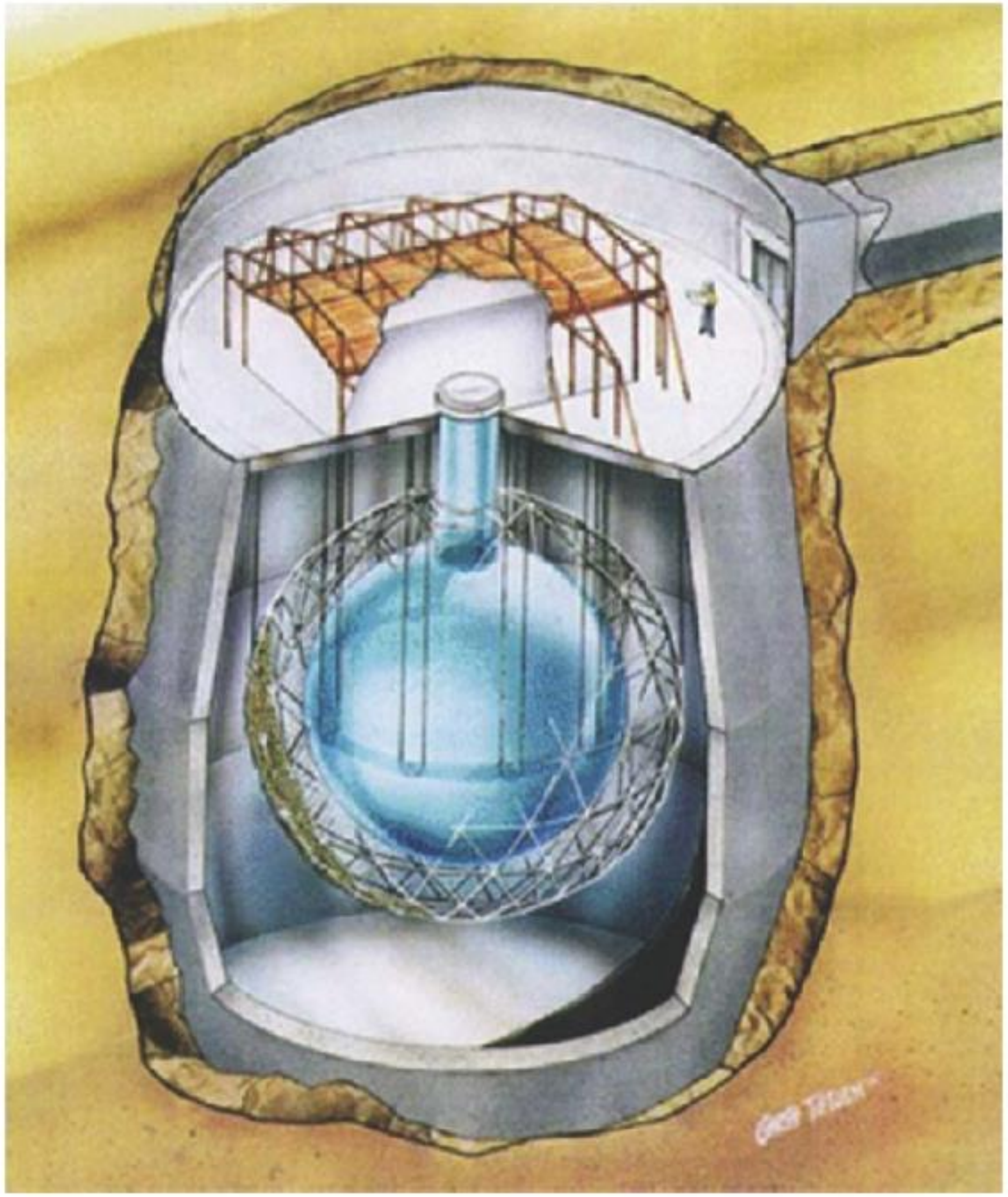
More data pointing to the “solar neutrino problem”

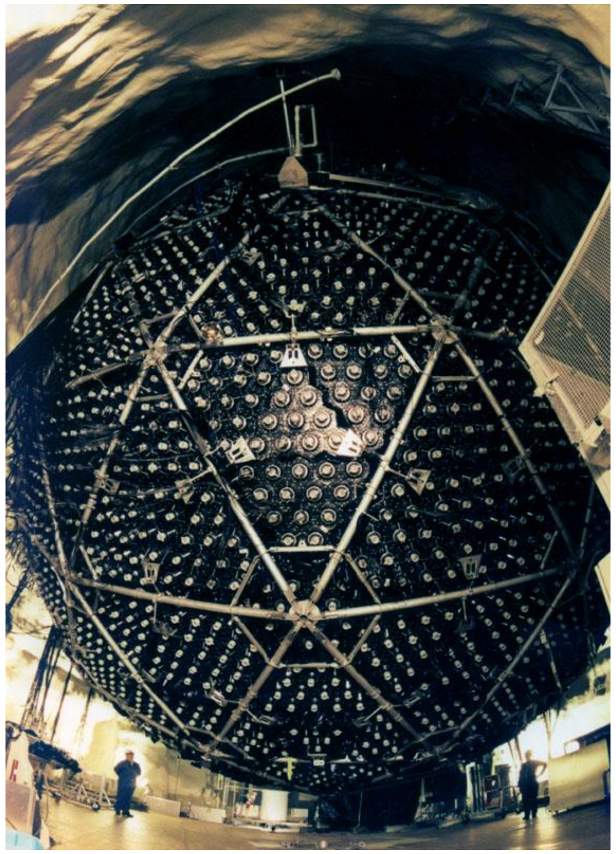


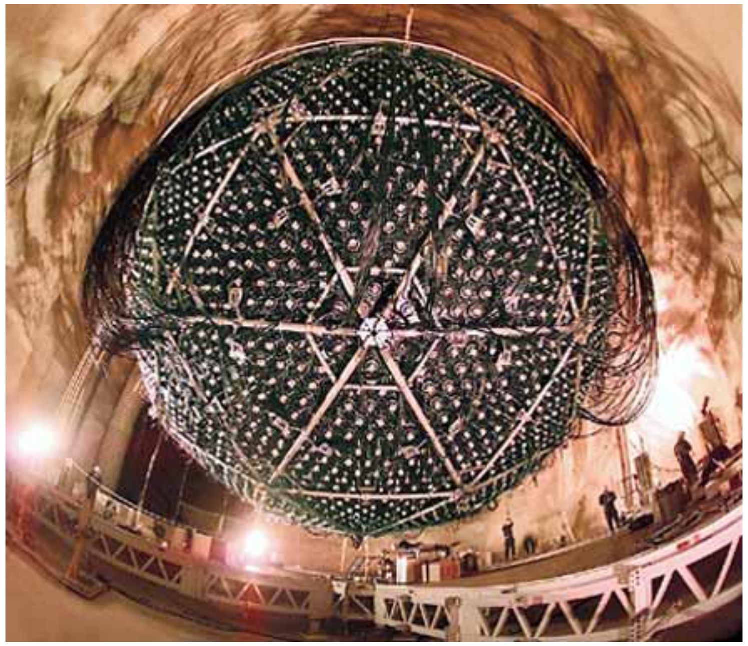
- **More experiments** observe the **solar neutrino deficit** at different neutrino energies:
  - **Water Cerenkov** detectors (e.g. SuperK)
  - **Gallium experiments** (GALLEX and SAGE)
- **Gallium** based experiments have a very low threshold (233keV) and are **sensitive mostly to pp neutrinos** (same concept as the Chlorine experiment, but Gallium based)

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

The Sudbury Neutrino Observatory







- SNO was built in the 90's, ~2km underground in Creighton mine, near Sudbury, Ontario, Canada
- It was filled with **~1000 tonnes of ultra pure heavy water (D_2O)** in the inner core. Standard water outside.
- Cerenkov radiation induced by electrons produced by solar neutrinos (with E>7MeV) was detected by 9600 PMTs

SNO's "secret" weapon

Being filled with heavy water, SNO can detect neutrinos through different reactions:

$$\nu_e + d \rightarrow p + p + e^-(CC)$$

sensitive to ν_e only, protons are below Cerenkov threshold and not observed. Threshold ~1.4MeV.

$$\nu_\alpha + d \rightarrow p + n + e^-(NC) \quad \alpha = e, \mu, \tau$$

sensitive to all neutrinos. The neutrons is then captured on deuterium, releasing a ~6.3MeV γ. Threshold 2.2 MeV.

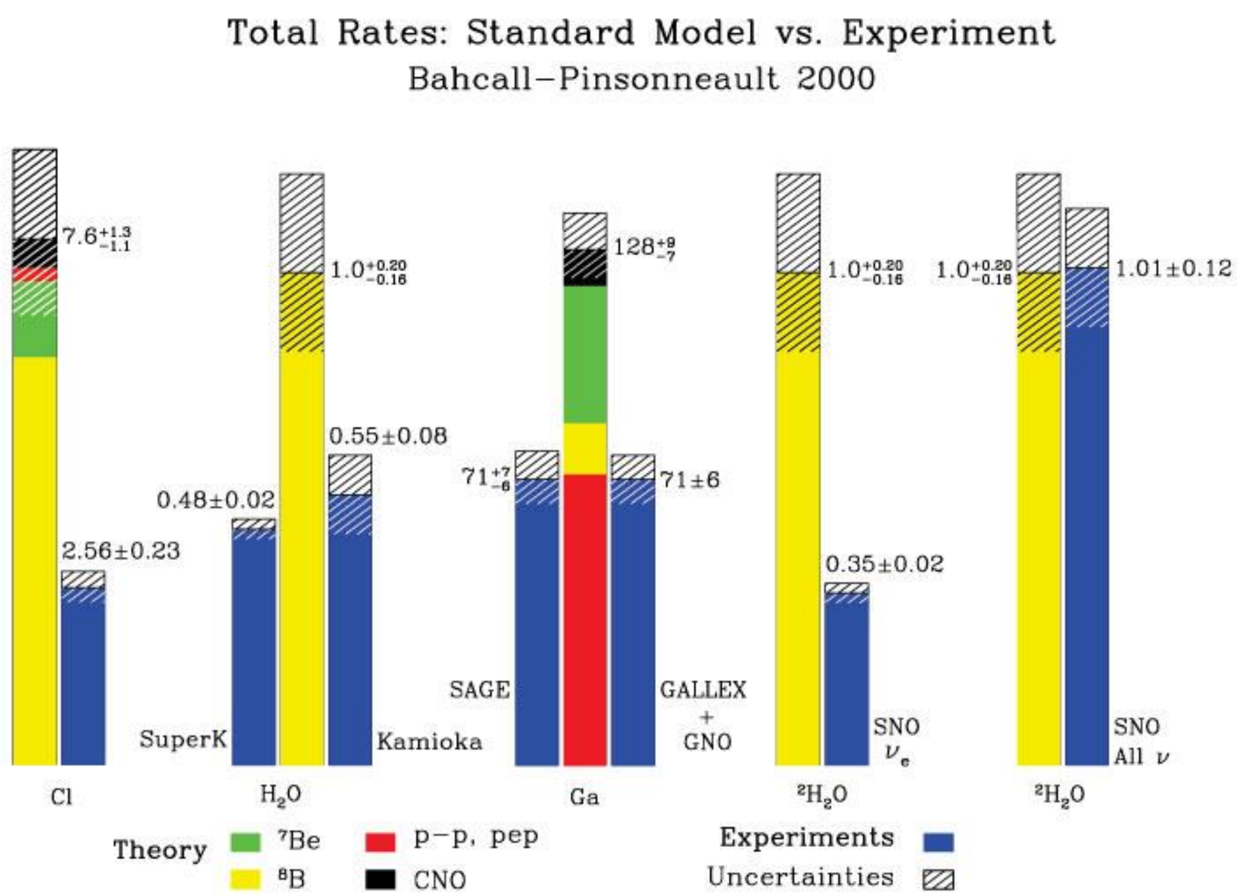
$$\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-(ES) \quad \alpha = e, \mu, \tau$$

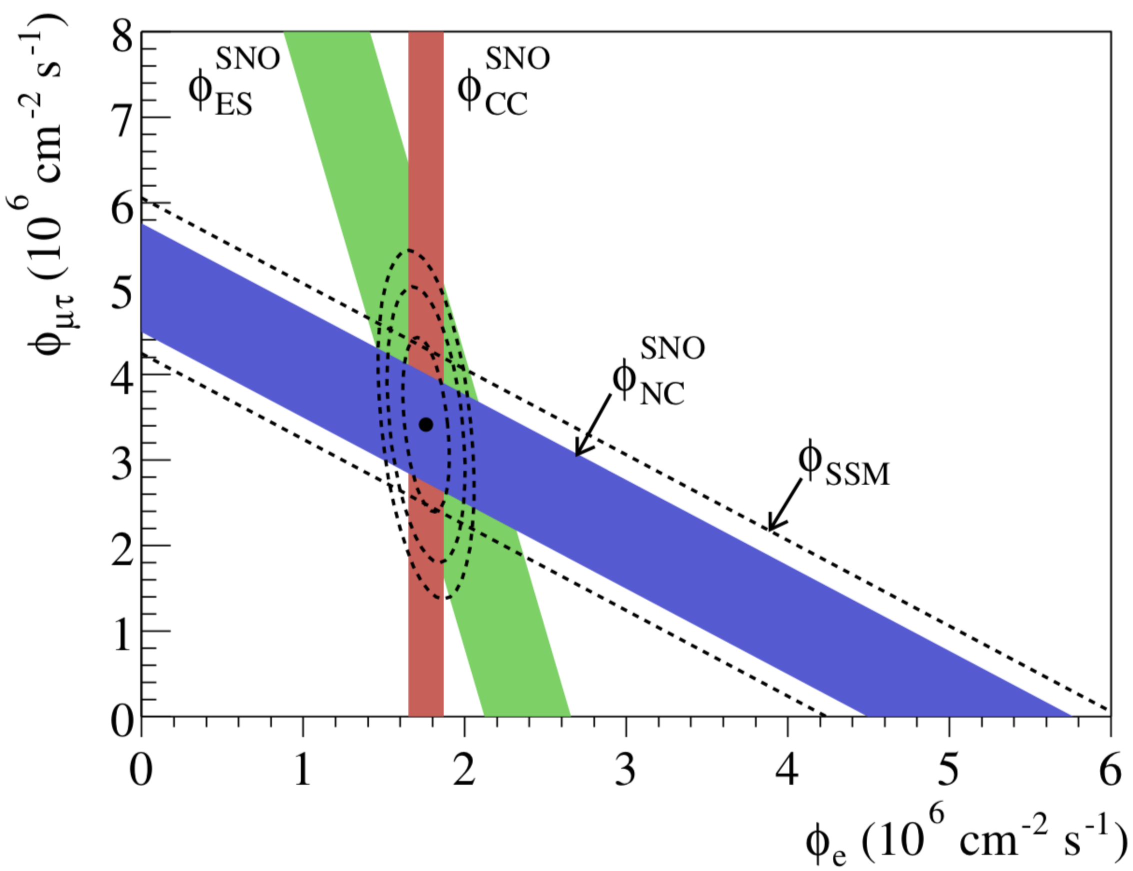
sensitive to all neutrinos, but most of the contribution comes from the CC channel for electron neutrino (6 times bigger than NC). Same rate in inner core filled with heavy water and outer core filled with regular water.

No threshold.

Later phases of the experiment used ^{35}Cl or ^{3}He in the inner core to enhance the neutron detection efficiency

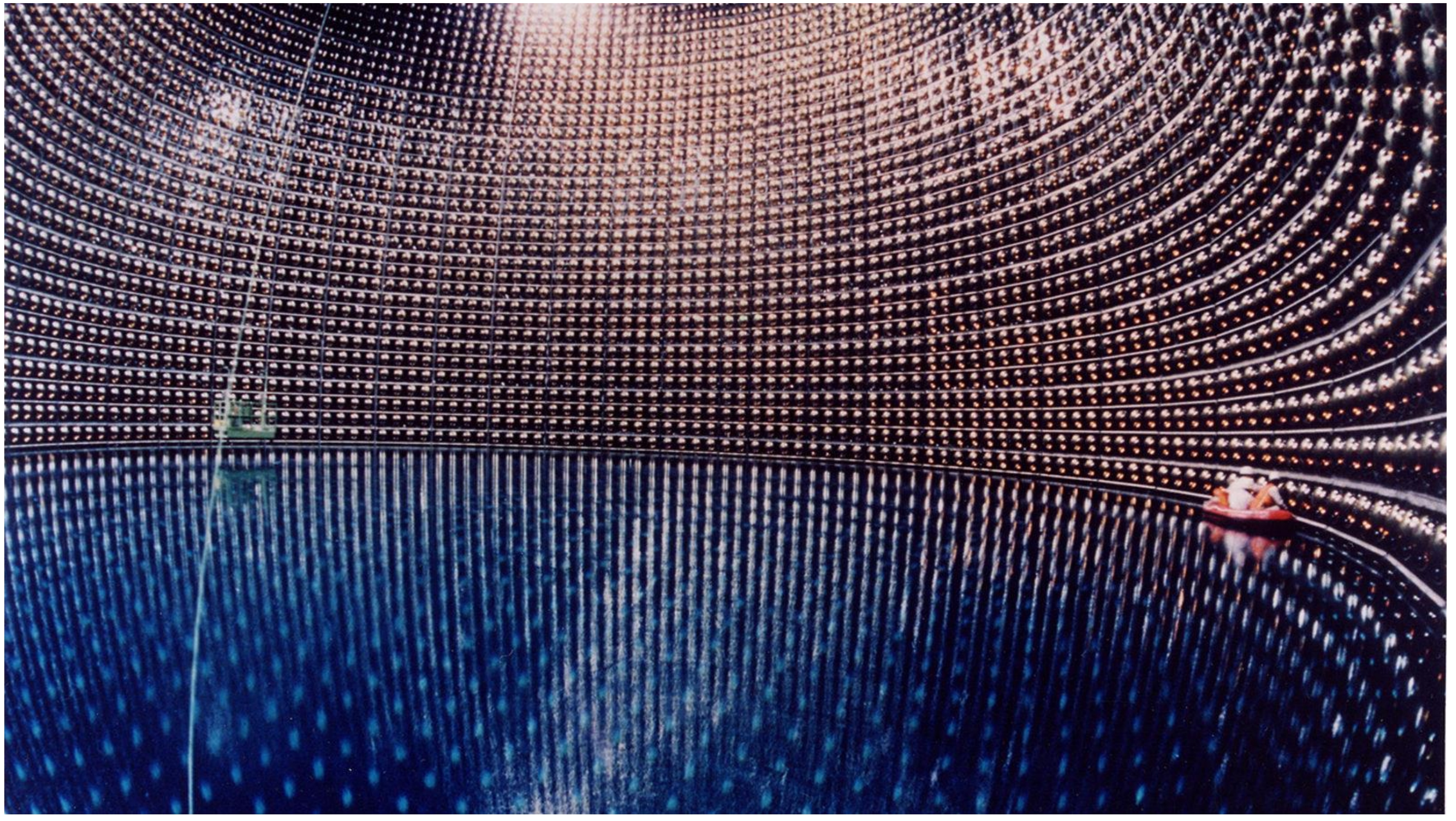
SNO's results





The neutrinos are there! Davis and Bahcall were both right.
"Simply", **they are not all electron neutrinos**

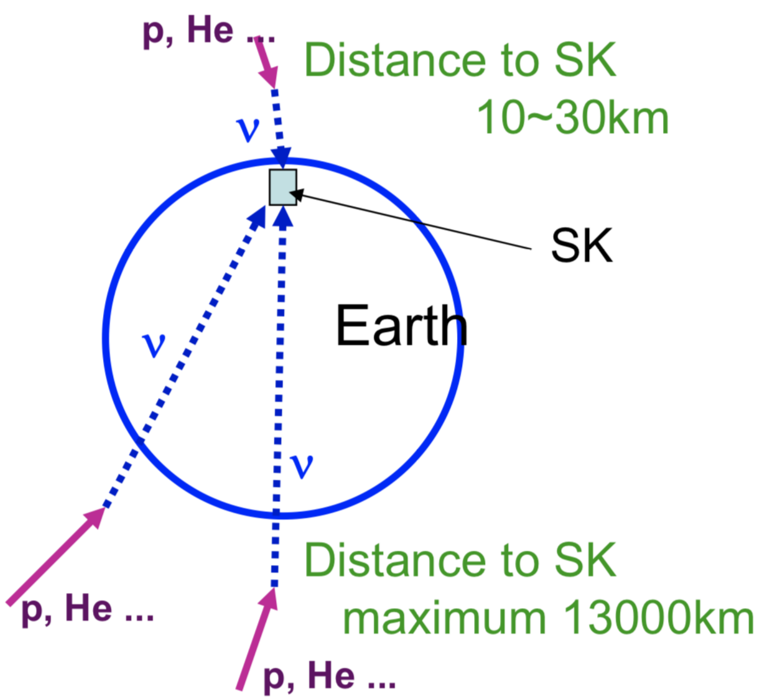
Super Kamiokande

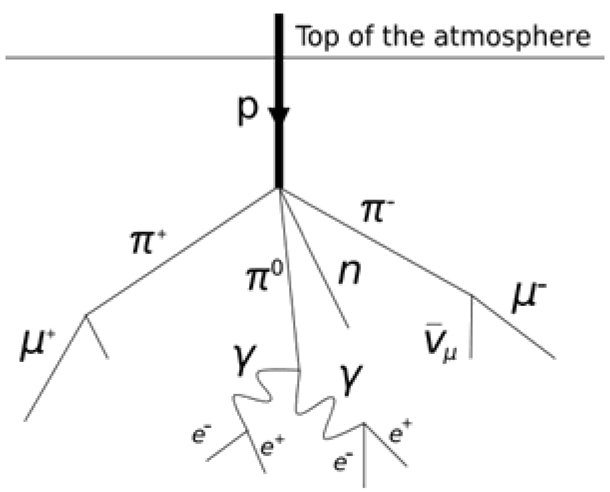


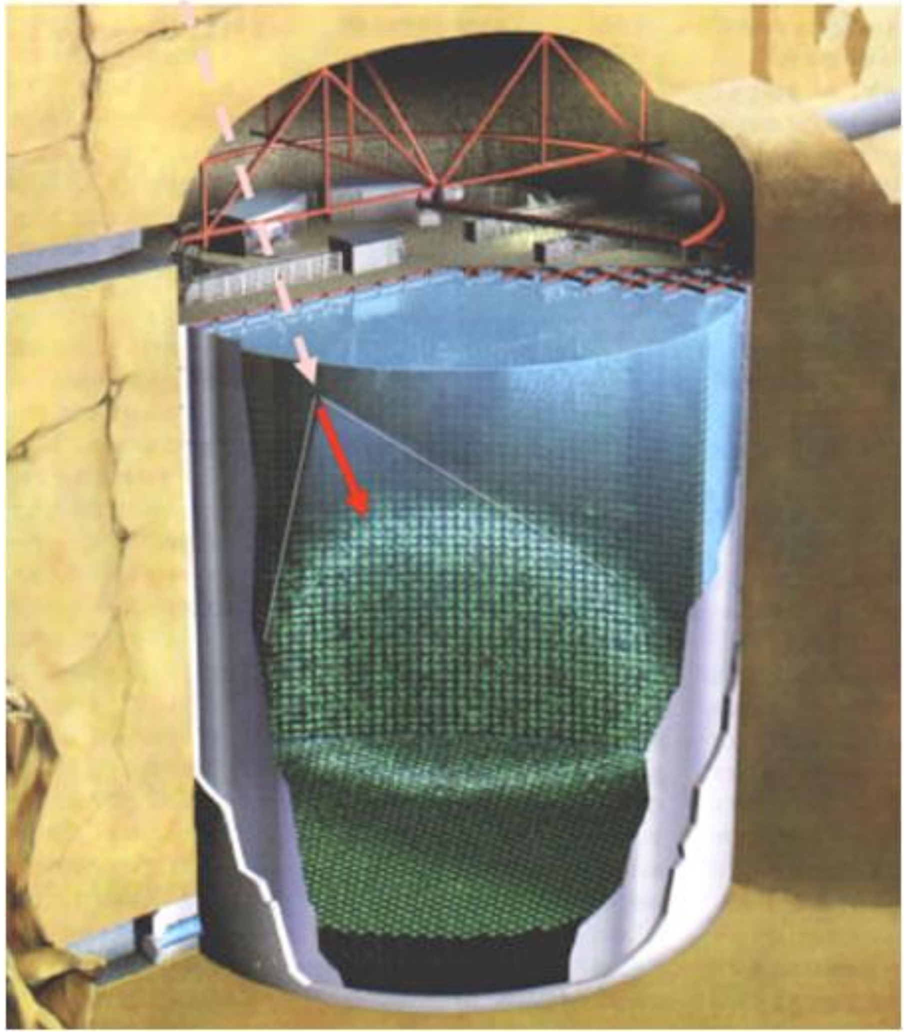
- In the 90’s, a 50kton ultra pure water Cerenkov detector was built ~1km underground in Kamioka’s mine
- Super-Kamiokande’s (Super-K) main purpose was **the search of proton decay**
- 11000 20’ PMTs look at Cerenkov rings from all directions in the water

Atmospheric neutrinos

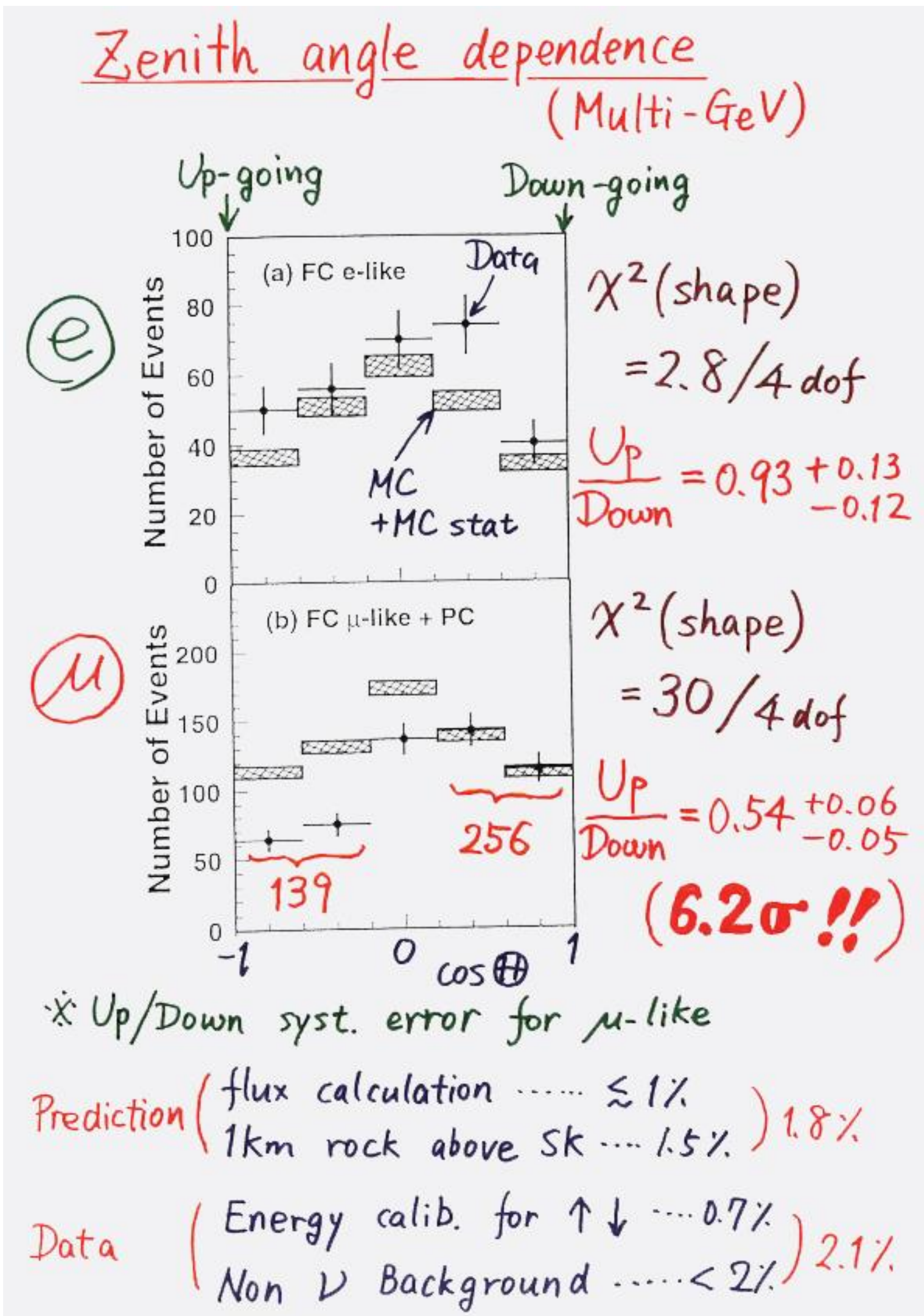
- Super-K also reported evidence of the solar neutrino problem and measured most precisely the ^{8}B solar neutrino flux
- One of the **backgrounds for the proton decay** search was due to **atmospheric neutrinos** (E~GeV), so it was critical to assess it
- Neutrinos produced on the other side of the Earth travel more distance before hitting Super-K with respect to those produced just above Japan

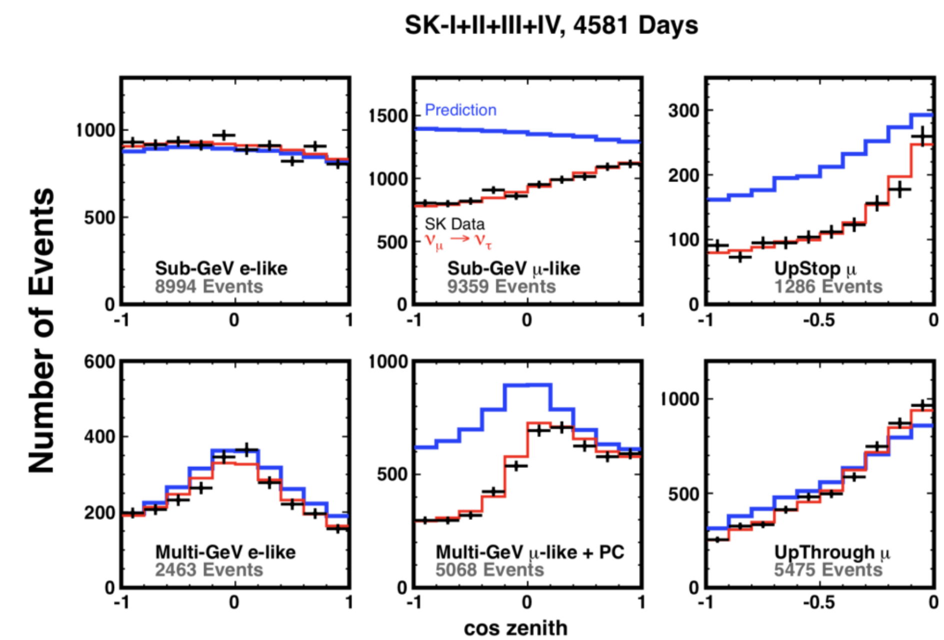






Super-K atmospheric results





- From T. Kajita's presentation at the conference "Neutrino 1998"
- **Up going muon neutrinos are suppressed** (electron neutrinos are not) with respect to down going
- Together with the solution of the solar neutrino problem, this is **evidence for neutrino oscillations!**

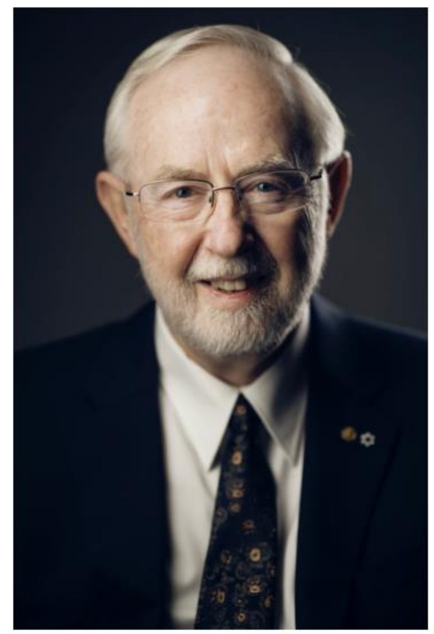
Another neutrino Nobel prize!

The Nobel Prize in Physics 2015

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2



© Nobel Media AB. Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

Neutrino mixing or something else?

- **Are SNO and Super-K results** (yet very important) **enough** to convince ourselves that neutrino oscillations are what is going on?
  - i.e. **is it the same physics generating both phenomena?**
- It could be some different physics beyond the SM…
- If neutrinos oscillate, **one must observe both disappearance and appearance**, in many different configurations
- I will try and explain why we need many neutrino oscillation experiments and why they are all different and important

New physics!

- The picture of neutrino oscillations and mixing now looks fairly well established…
- Nonetheless, **this is the only evidence (so far) of physics beyond the Standard Model!**

Q: “What gives you hope that we could achieve anything like what you guys achieved in constructing the Standard Model today?”

A. “The obvious answer is neutrino masses, which I think clearly take us beyond the standard model, and clearly represent something coming down from a very high energy scale.”

Stephen Weinberg at the SLAC summer institute earlier this summer

Leptonic mixing

Lepton flavors are superpositions of mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Convenient parameterization:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

“atmospheric” **“reactor”** **“solar”** **“Majorana”**

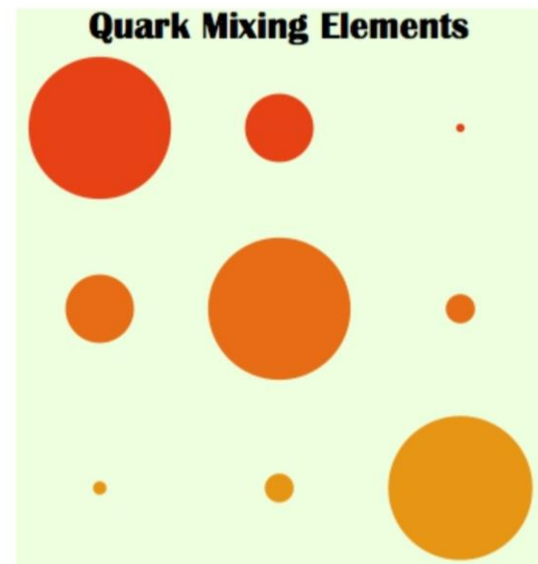
U is unitary, and being 3x3 has, as free parameters:

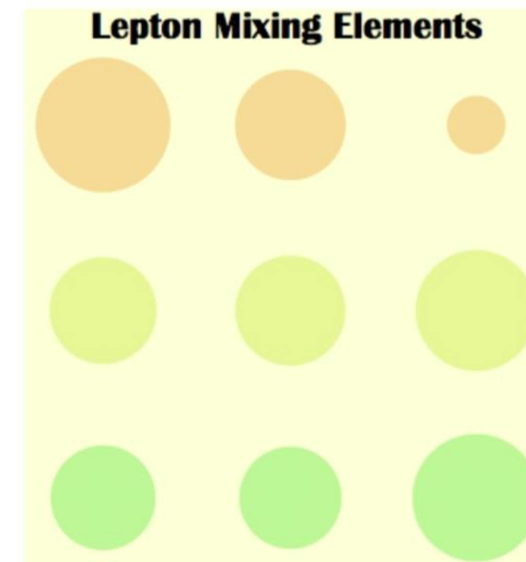
- 3 angles + 1 CP violating phase if neutrinos are Dirac particles
- 3 angles + 1 CP violating phase + 2 Majorana phases if neutrinos are Majorana

Oscillations are not sensitive to α_1 and α_2!

More on the PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

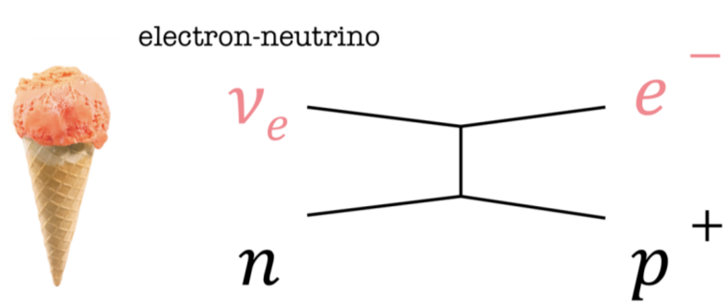


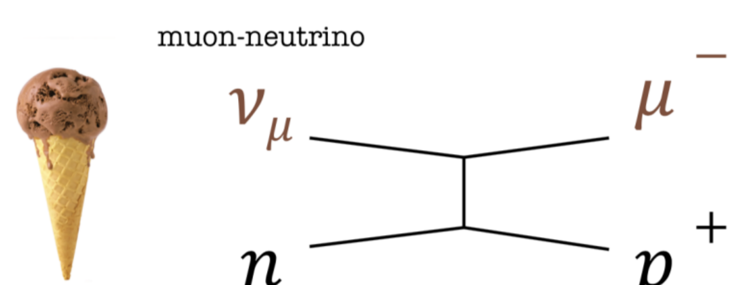


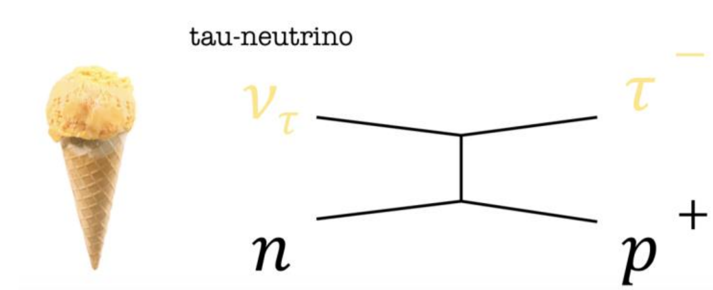
Mixing in the lepton sector is large!

Understanding the PMNS matrix:

1. The “e row” gives the linear combination of mass eigenstates that couple to ν_e
2. The “1 column” shows the linear combination of charged lepton mass eigenstates that couple to ν_1







Oscillation probability

$\alpha = \beta \Rightarrow$ *"disappearance"*

$\alpha \neq \beta \Rightarrow$ *"appearance"*

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

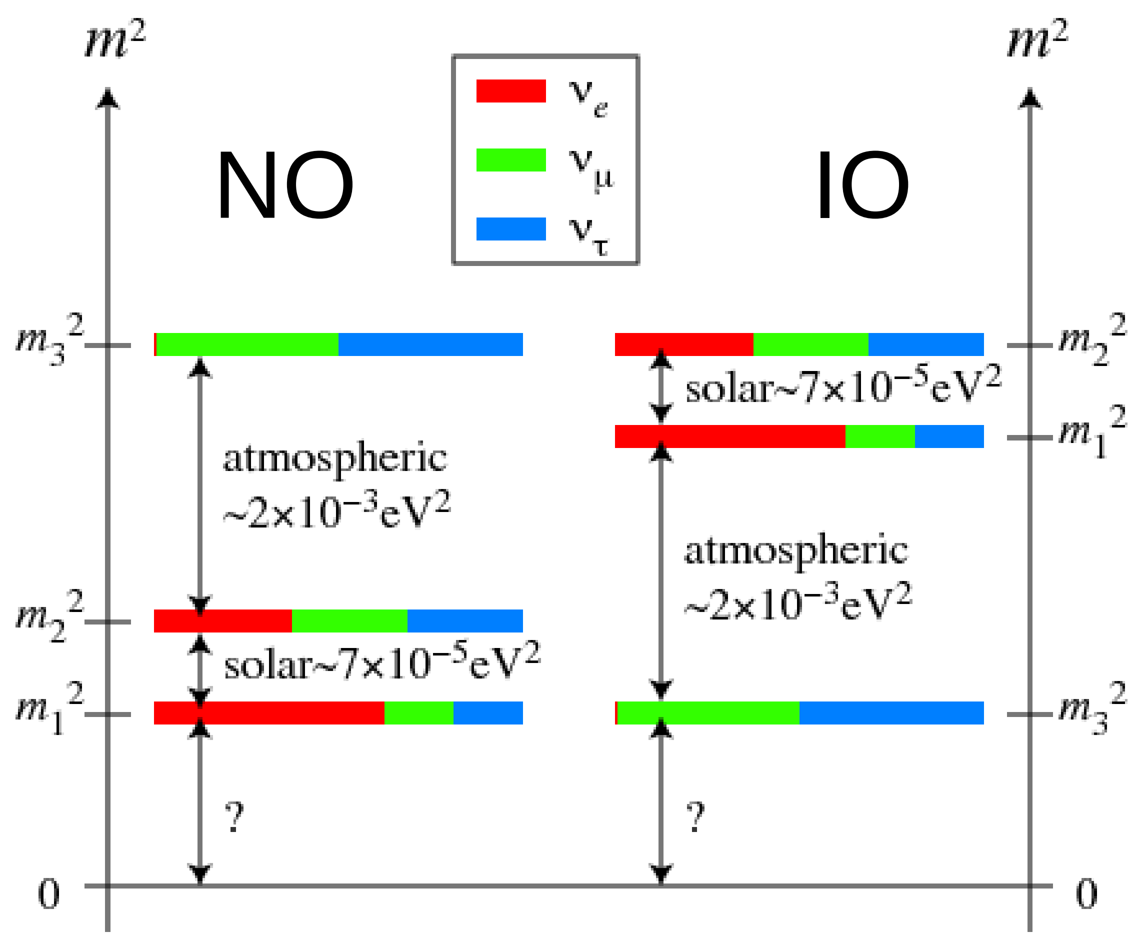
$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

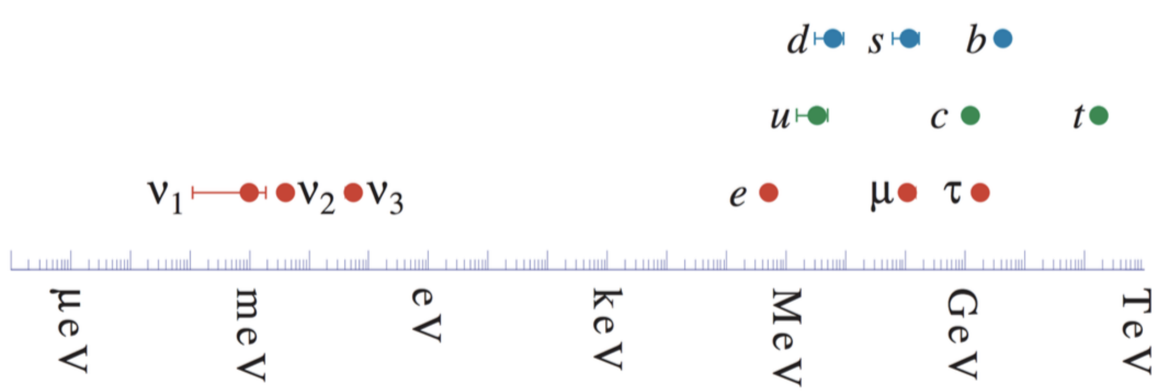
$$\Delta m^2_{ij} = m^2_i - m^2_j \qquad \frac{\Delta m^2_{ij} L}{4E} \approx 1.267 \frac{\Delta m^2_{ij} [eV^2] \times L[km]}{E[GeV]}$$

Neutrino oscillations require neutrino masses*

*technically, NSI would also make the trick, but the huge phenomenology observed is difficult to explain with NSI.

What do we know about neutrino masses?





- Two possibilities are open, depending on the sign of Δm_{23}^2:

1. **Inverted Ordering** (or Inverted Hierarchy, historically)
2. **Normal Ordering** (of Normal Hierarchy)

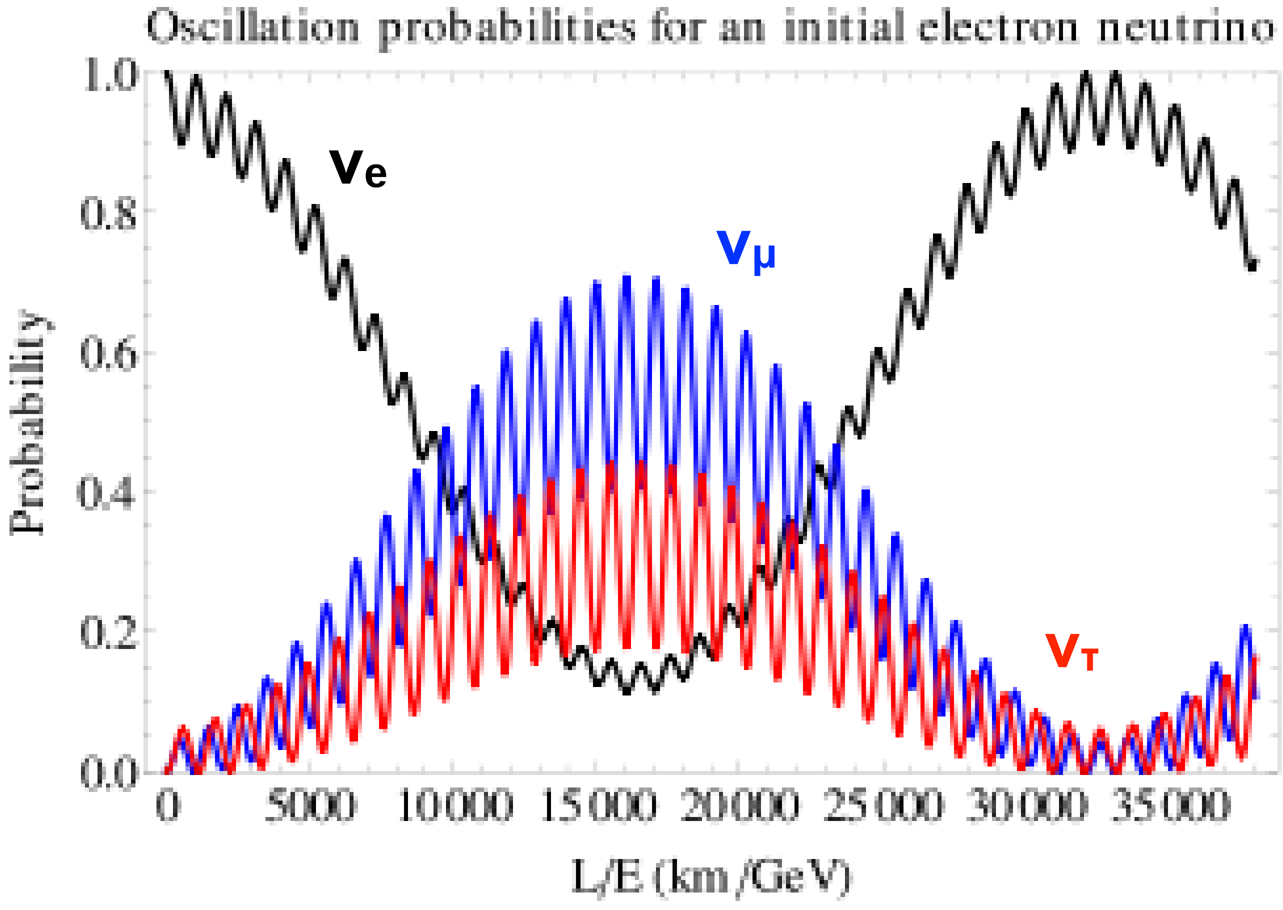
We know neutrino masses are tiny (the sum is less than ~0.2 eV) but **we do not know which is the absolute mass scale**

- oscillations cannot probe it

Why are neutrino masses so small? What mechanism generate them? A Yukawa coupling to the Higgs? Something else?

A look at neutrino oscillations

- **The critical parameter is L/E**
- The mass splitting determines the frequency of oscillations in L/E
- The mixing angle determines the amplitude of the oscillation



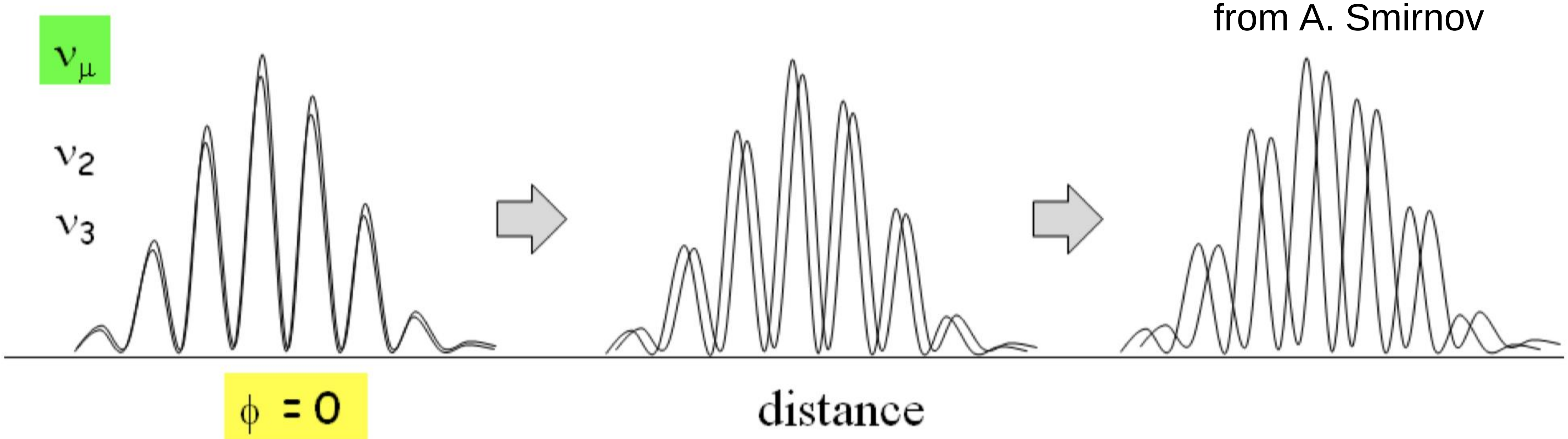
2 oscillation frequencies, one for each mass splitting:
the "fast component" is due to Δm_{23}^2
the "slow component" is due to Δm_{12}^2

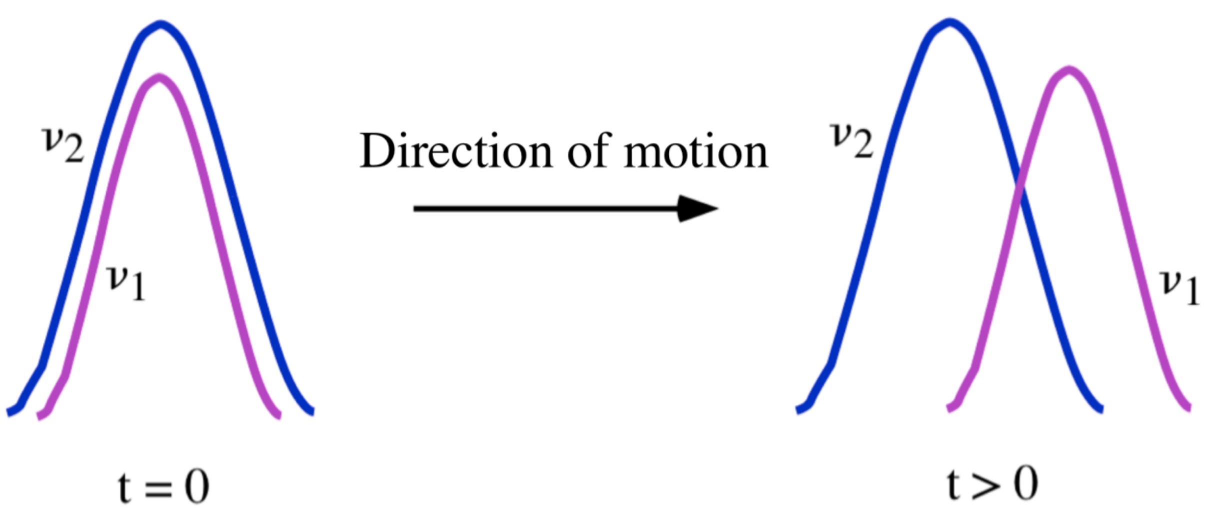
Since the 2 splittings are so different, one can conveniently use a **2 flavor oscillation approximation** in many practical cases, neglecting the effects induced by one of the splittings

$$\frac{1.267\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})} \approx \frac{\pi}{2} \Longrightarrow \frac{\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})} \approx 1.$$

Oscillations and coherence loss

from A. Smirnov





from B. Kaiser

- Eventually the wave packets will separate: NO more oscillations!!!
- This happens **on a scale of 10^{20} km for accelerator neutrinos, and 10^{3} km for SuperNova neutrinos**

Current knowledge on leptonic mixing

Precision measurements

https://globalfit.astroparticles.es/

parameter	best fit $\pm$ 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

A slide from M. Tortola's talk at Neutrino 2018 in Heidelberg last June

Are we done?

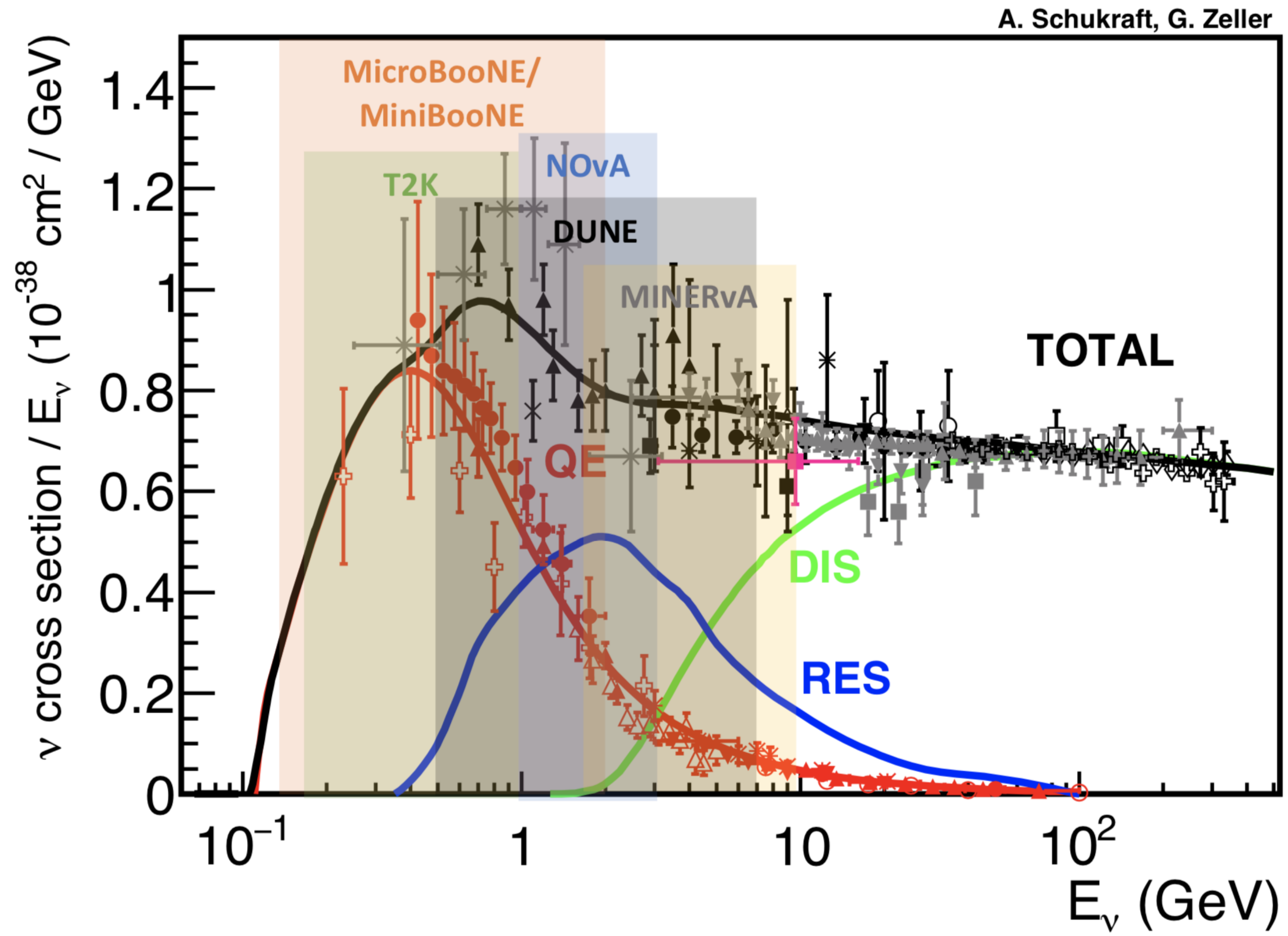
- …how did we get that knowledge?

- First of all, **both solar (SNO) and atmospheric neutrino oscillations (Super-K) had to be confirmed independently**

- **Many experiments with different L/E** are needed to be sensitive to the various oscillation parameters and mass splittings

- What is left to be discovered and measured?

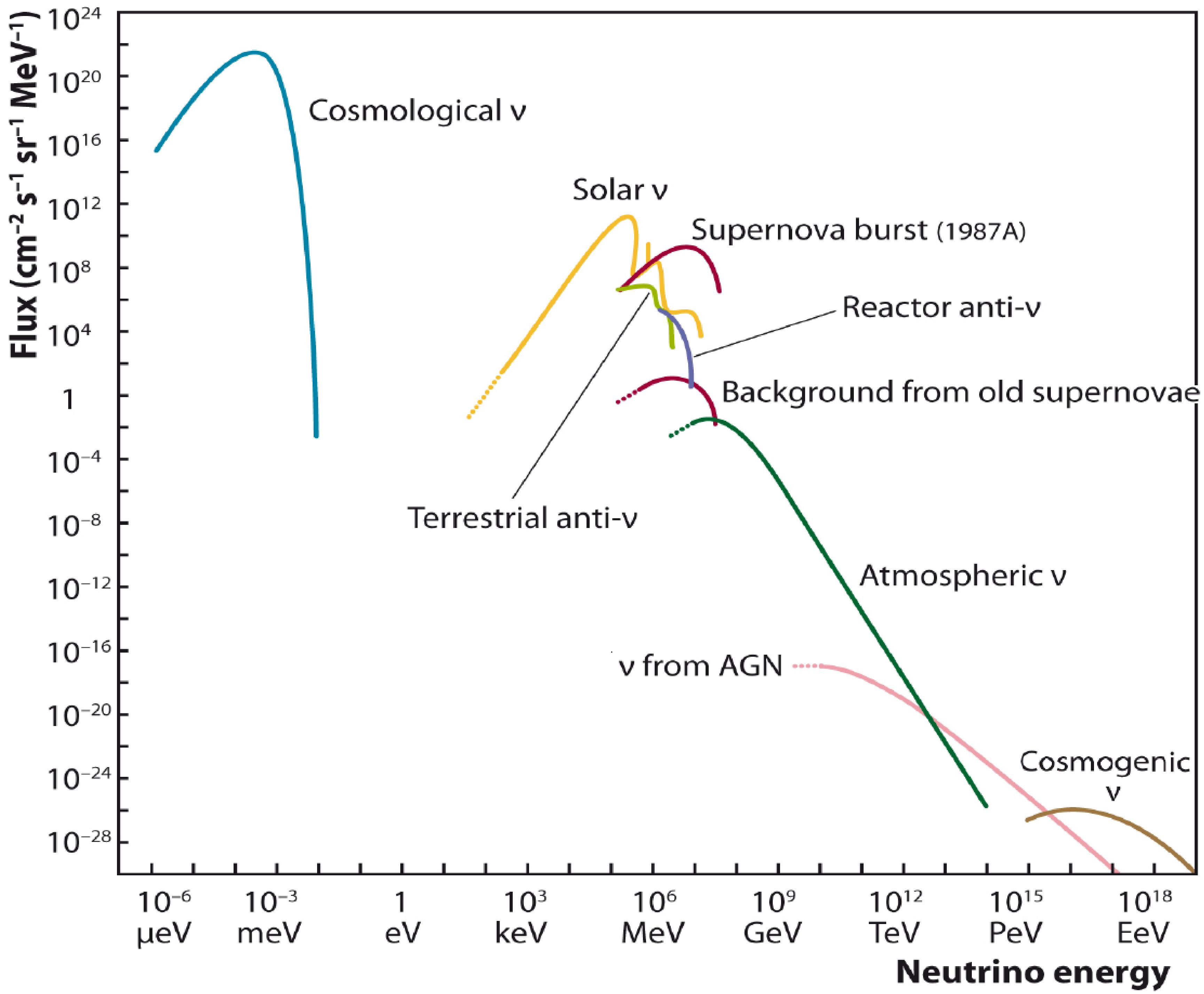
Neutrino Cross Sections



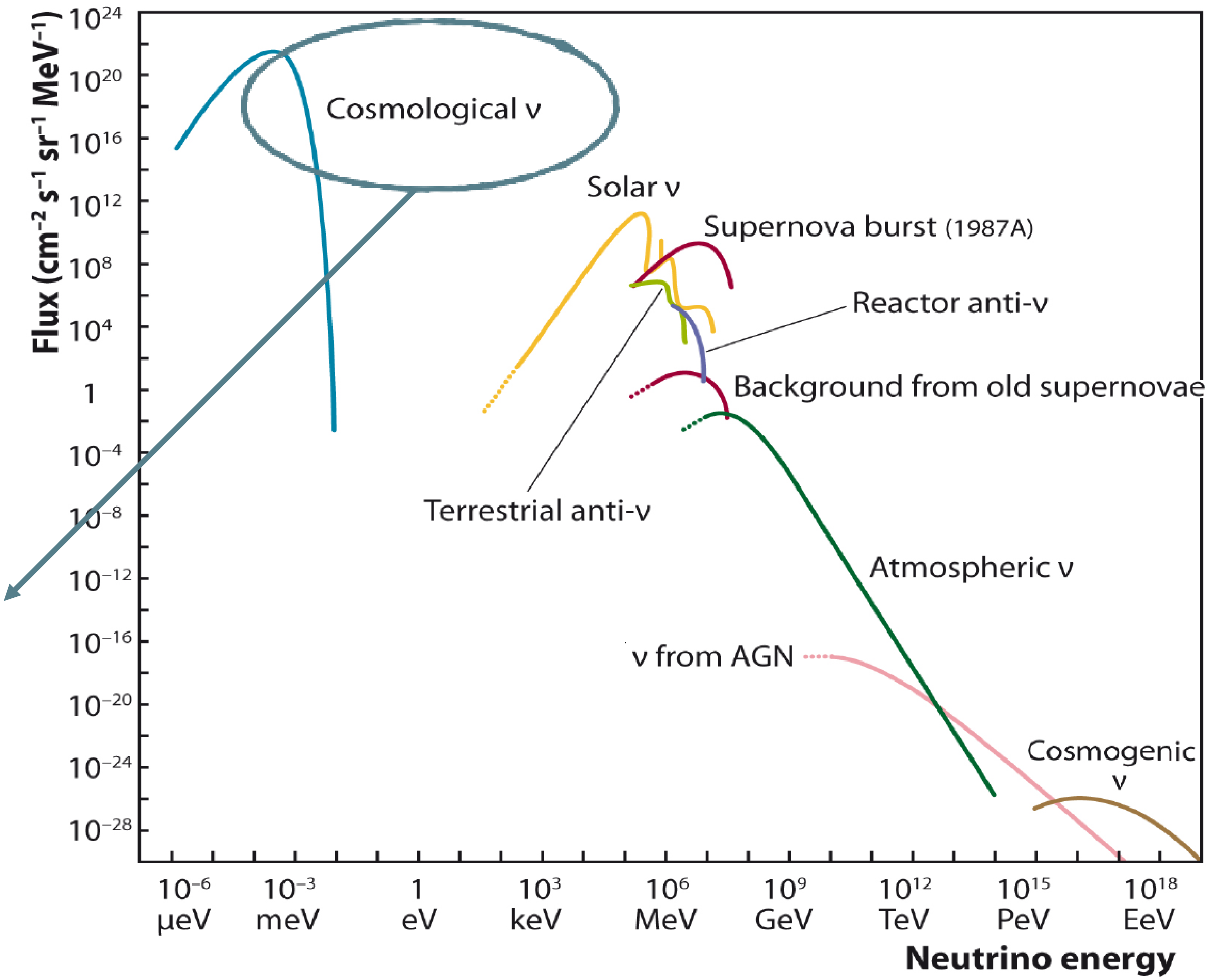
- Neutrino interactions can be complicated (we will touch this tomorrow)
- The only point I want $\sigma \simeq \frac{2 m_e G_F^2 E_\nu}{\pi} = \frac{G_F^2 s}{\pi}$ **is proportional to E_ν**

See Formaggio & Zeller, https://arxiv.org/pdf/1305.7513.pdf

Neutrino sources



Neutrino sources



relic of the Big Bang

T~1.9K

not yet observed directly

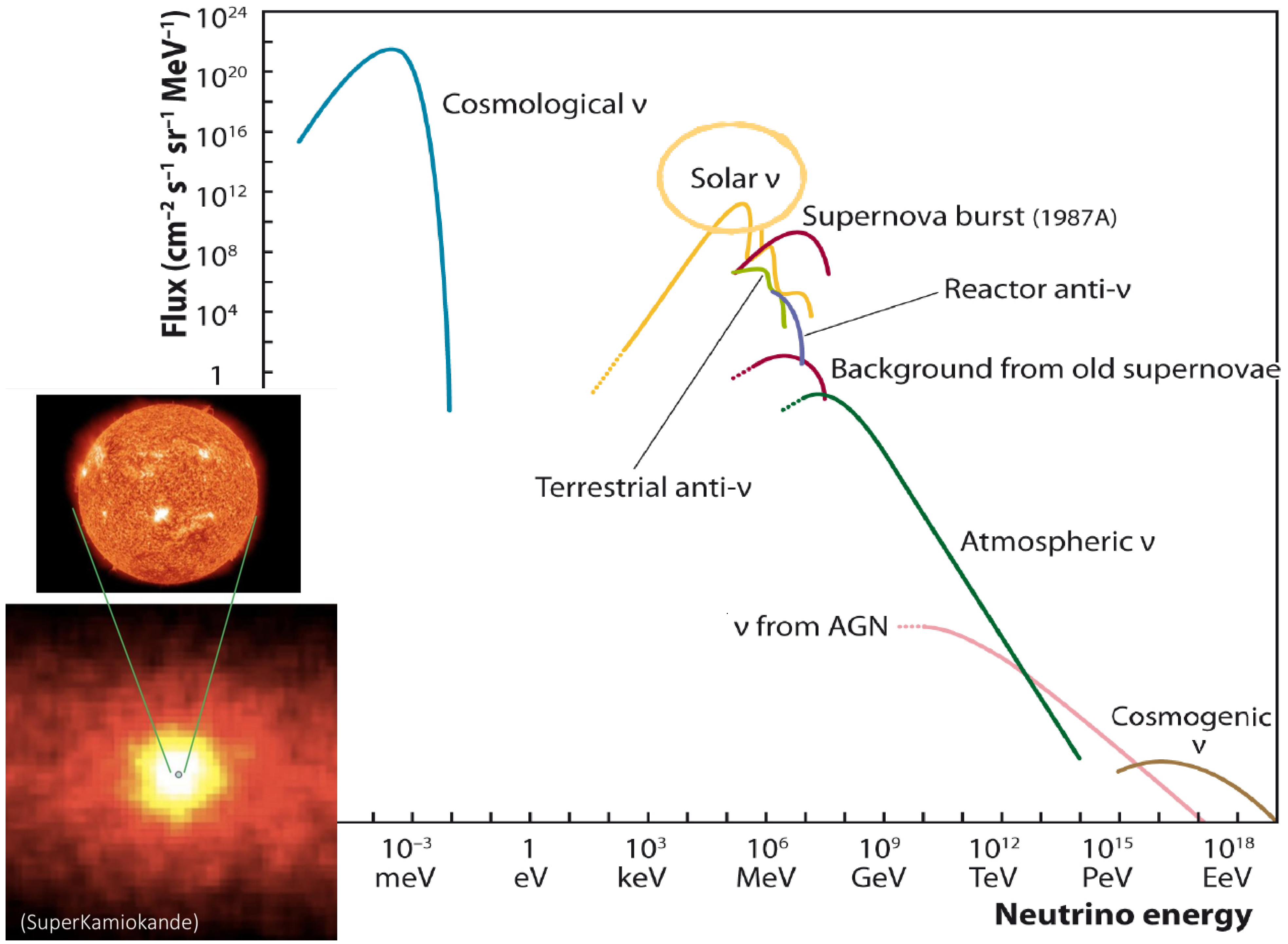
~300 ν/cm^3

…30 10^6 inside you!

But they are non relativistic, so difficult to observe.

not useful for oscillation searches!

Neutrino sources



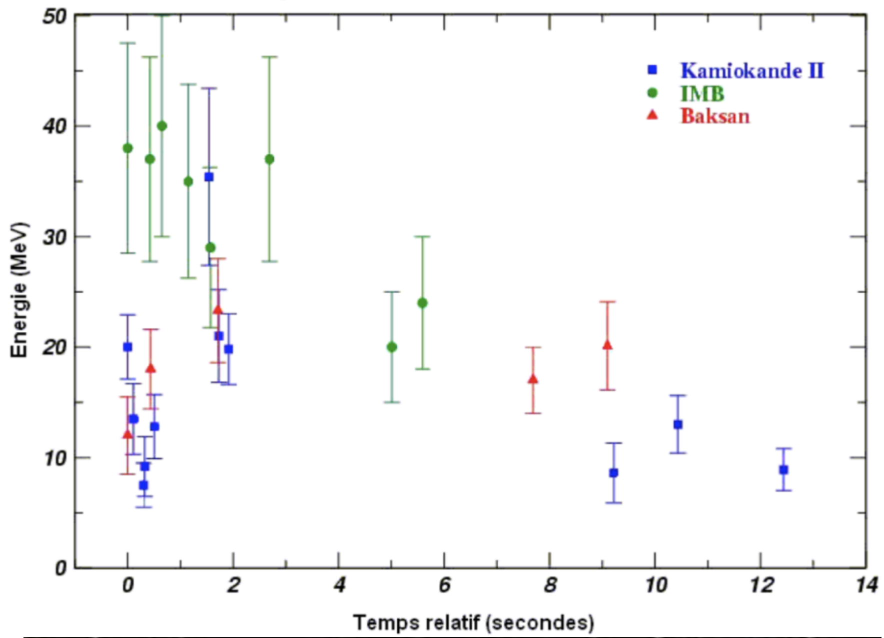
Huge flux (60 billions per second in your finger tip)

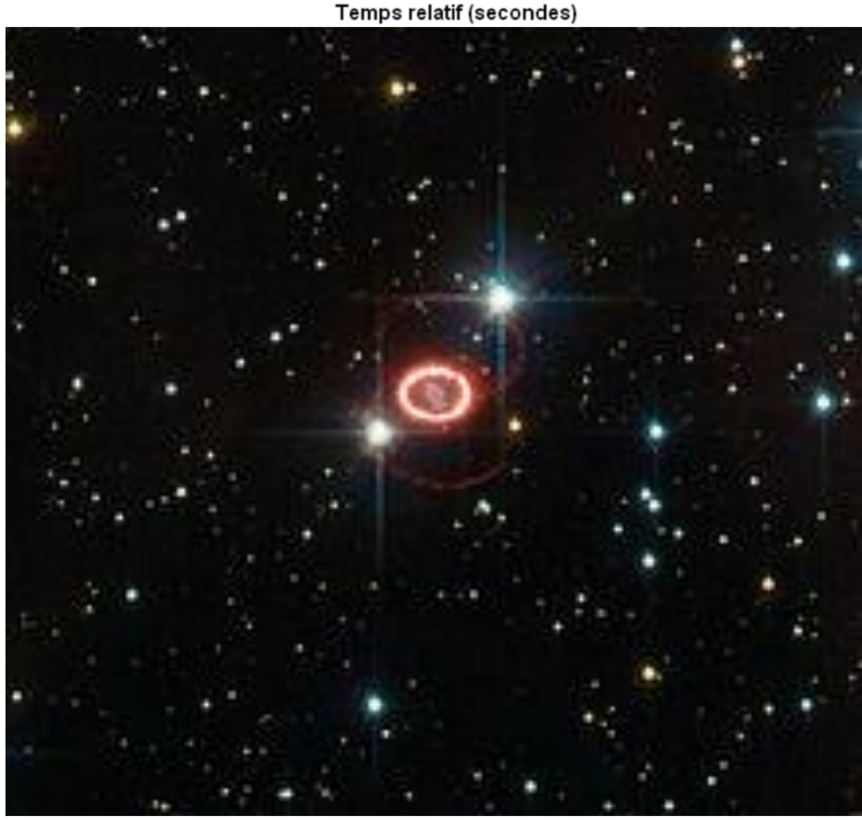
We can't decide L/E

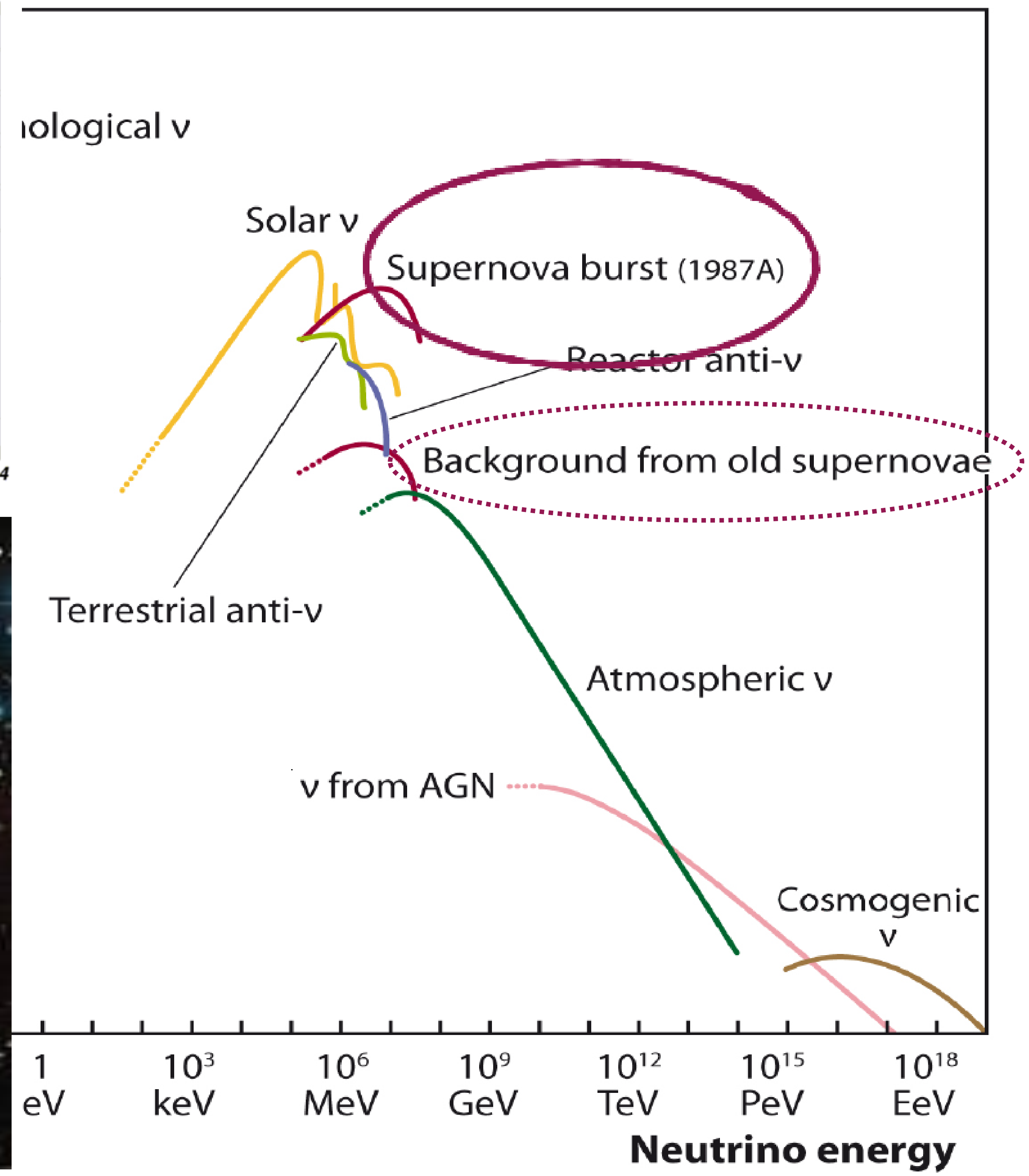
✔

good for leptonic mixing studies

Neutrino sources







100k times brighter than the Sun in neutrinos…

1-3 per century in our galaxy?

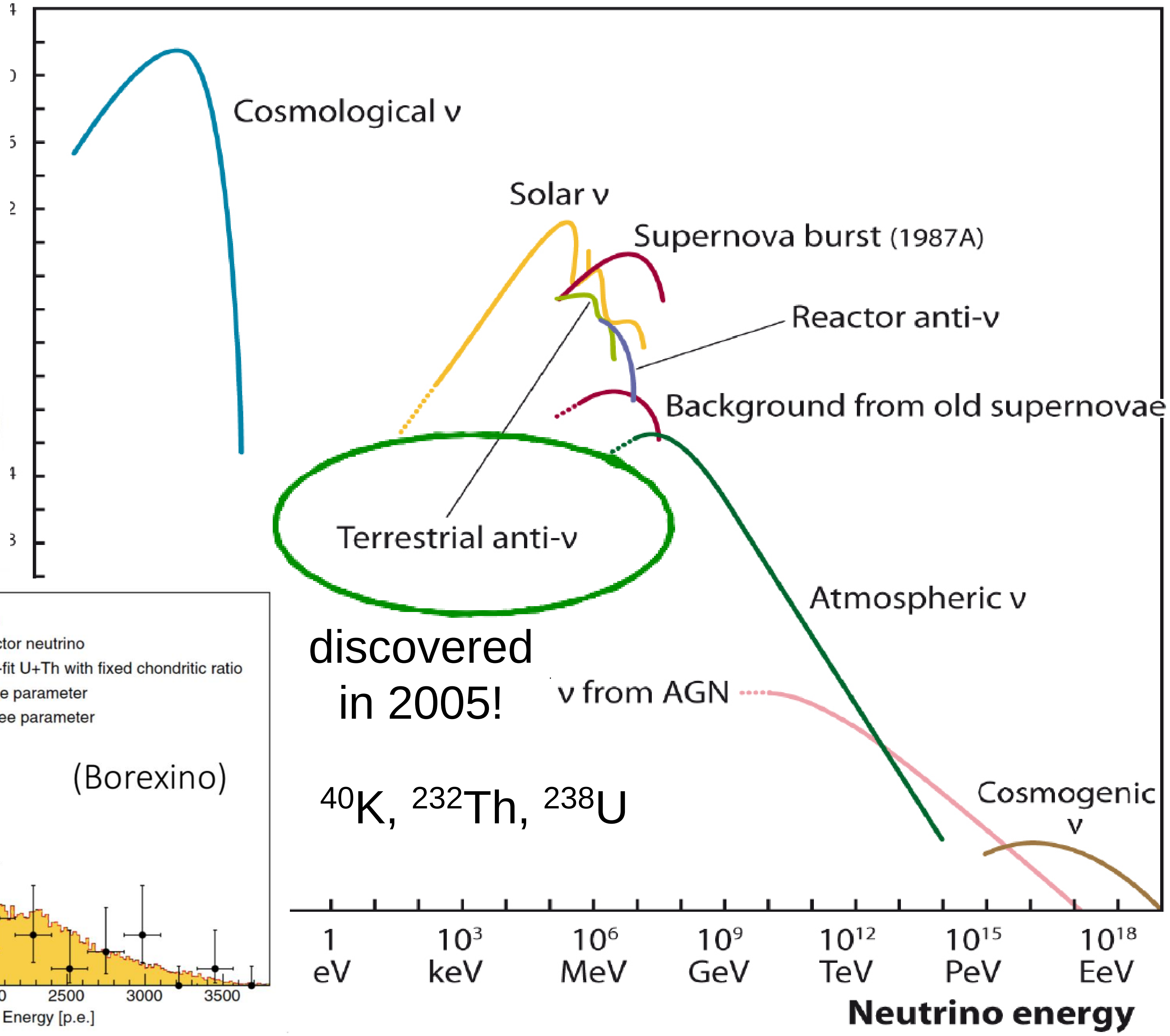
The source is unknown, and coherence is lost!

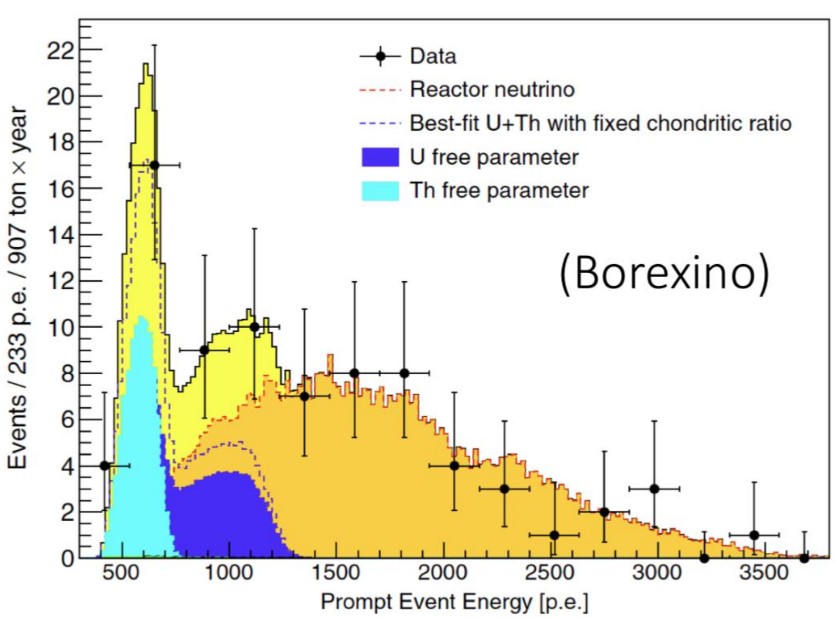
not useful for oscillation searches!

Neutrino sources

358 mg / 100gm
-> 1 million neutrinos/day

485 mg / 100gm





discovered in 2005!

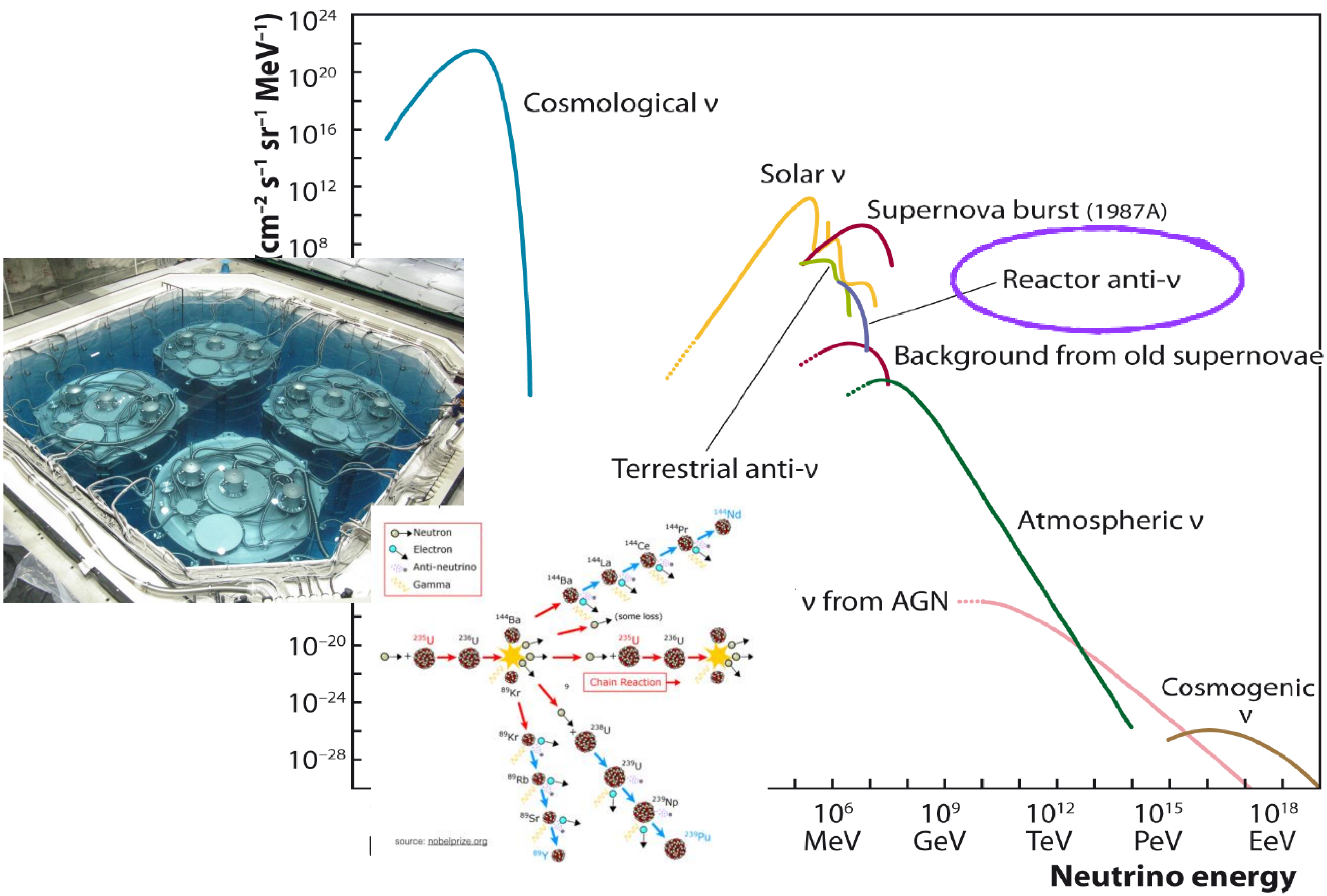
^{40}K, ^{232}Th, ^{238}U

baseline (L) unknown

low flux at relatively low energy

not useful for oscillation searches!

Neutrino sources



Powerful and with a large neutrino flux (Reins and Cowan!)

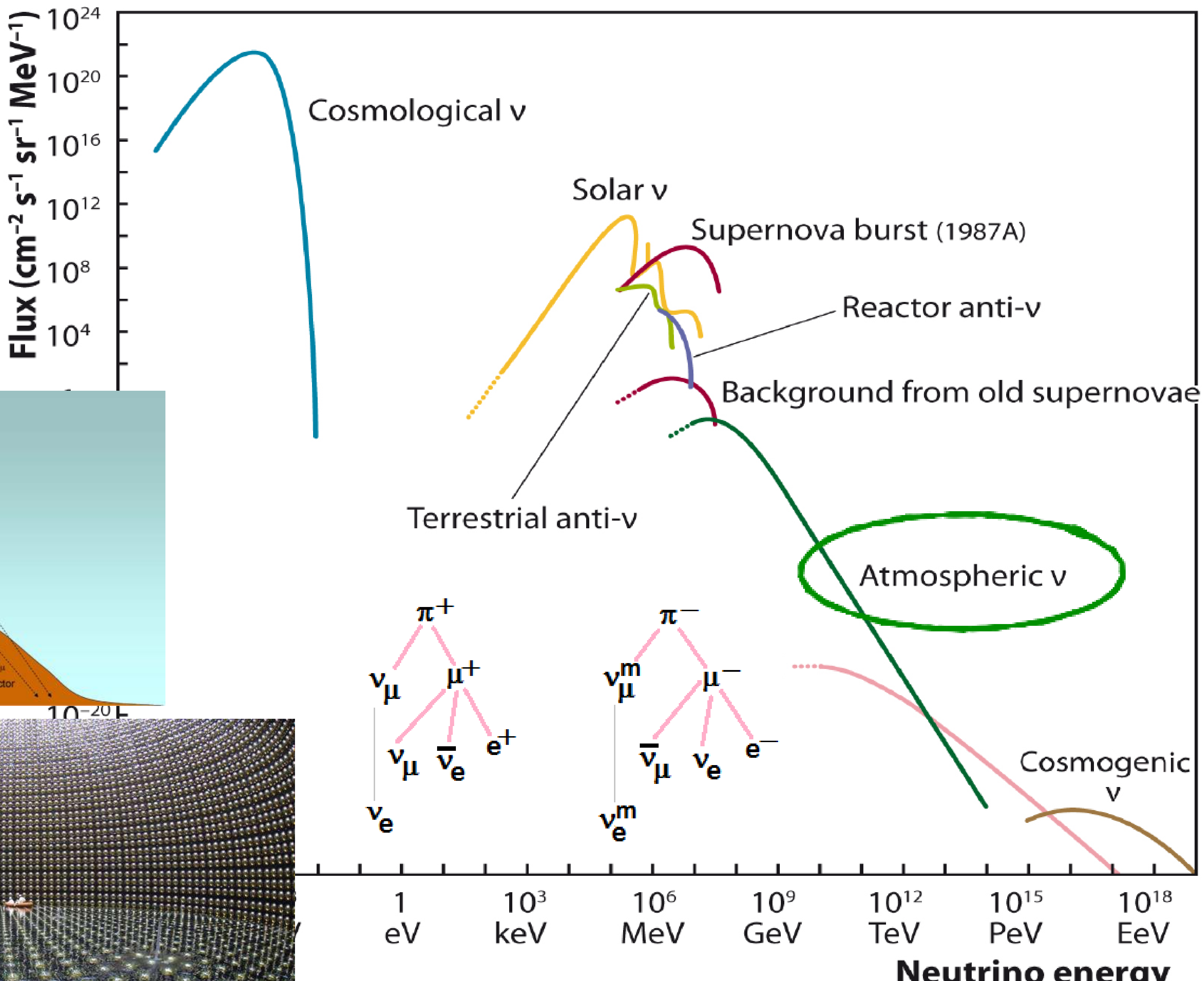
~6 $\overline{\nu}_e$ per fission (200MeV)

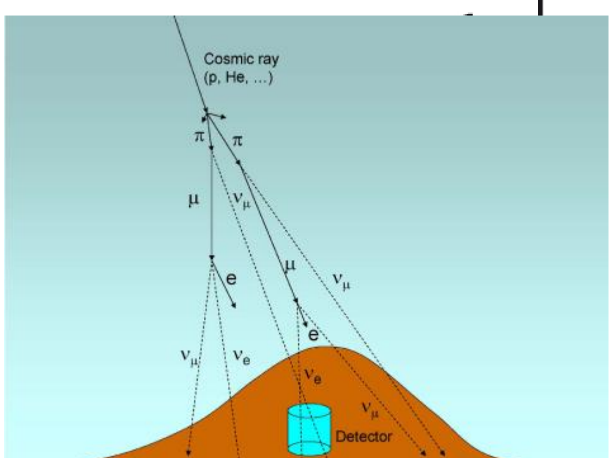
You can ~ pick the distance from the reactor core

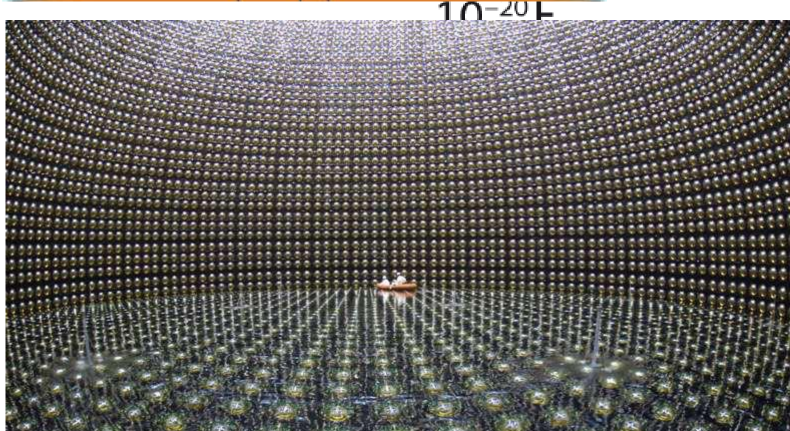
✓

good for oscillation searches

Neutrino sources







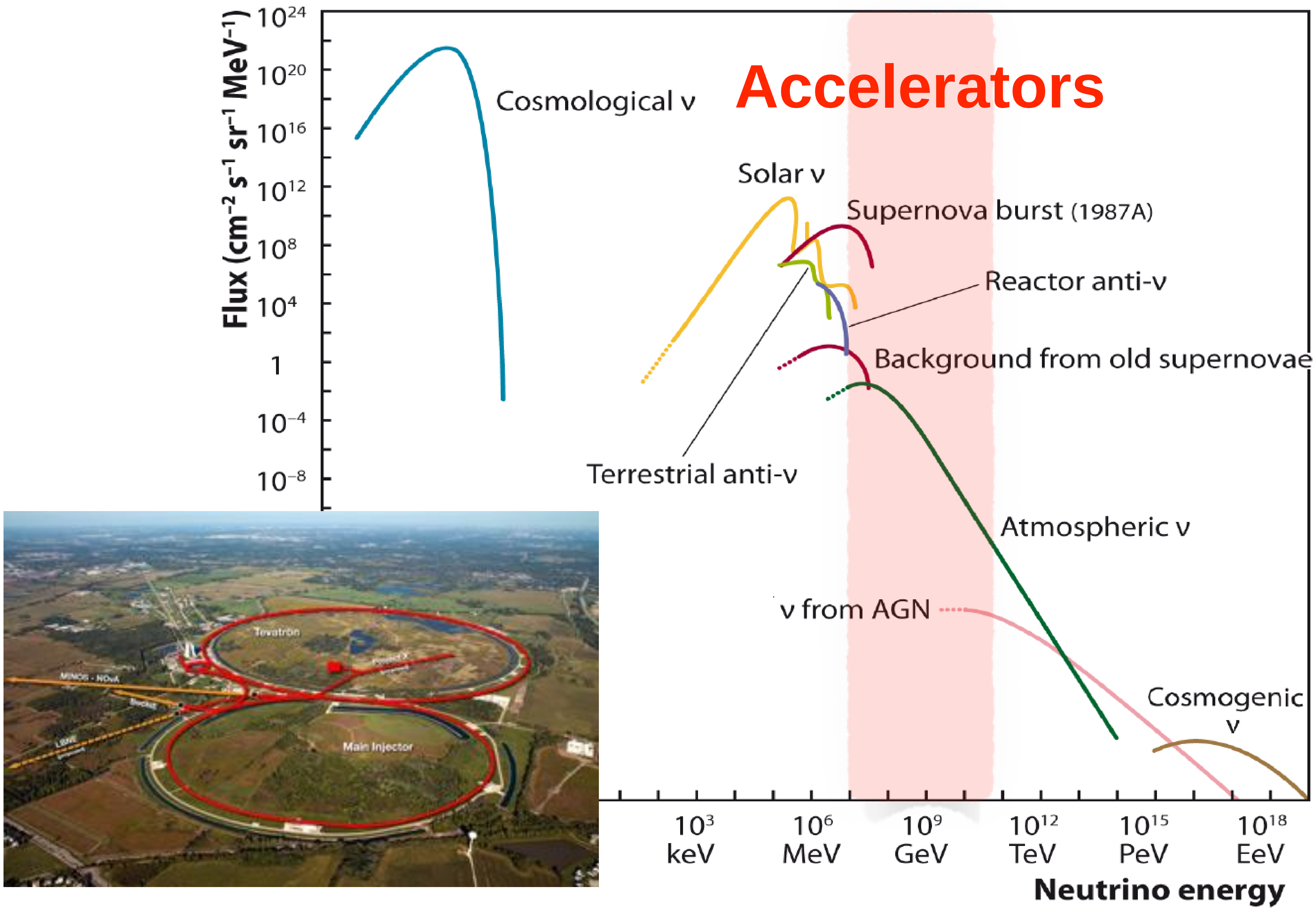
Reasonably large flux at ~high energy

Different L/E depending on the zenit angle

✔

good for oscillation searches

Neutrino sources

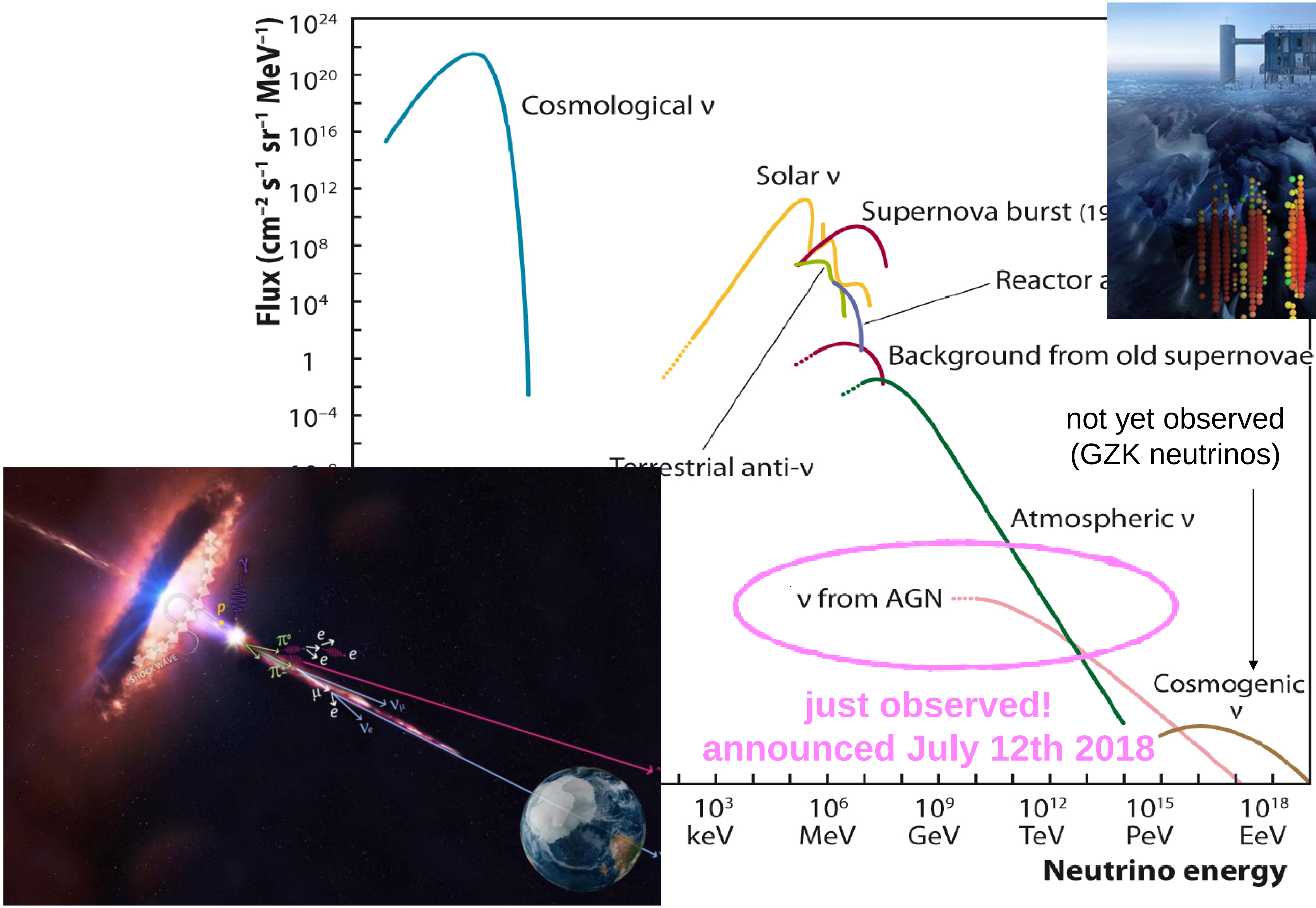


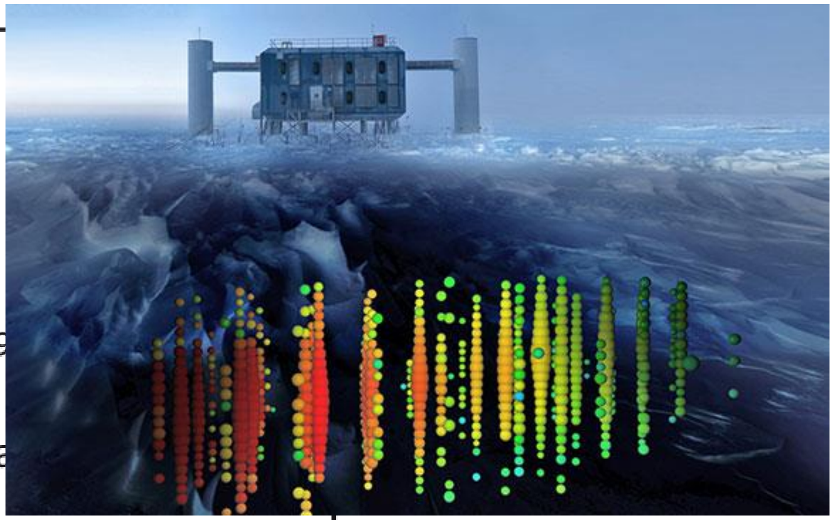
Very large flux, with controlled intensity, energy spectrum and baseline!

✓

good for oscillation searches

Neutrino sources





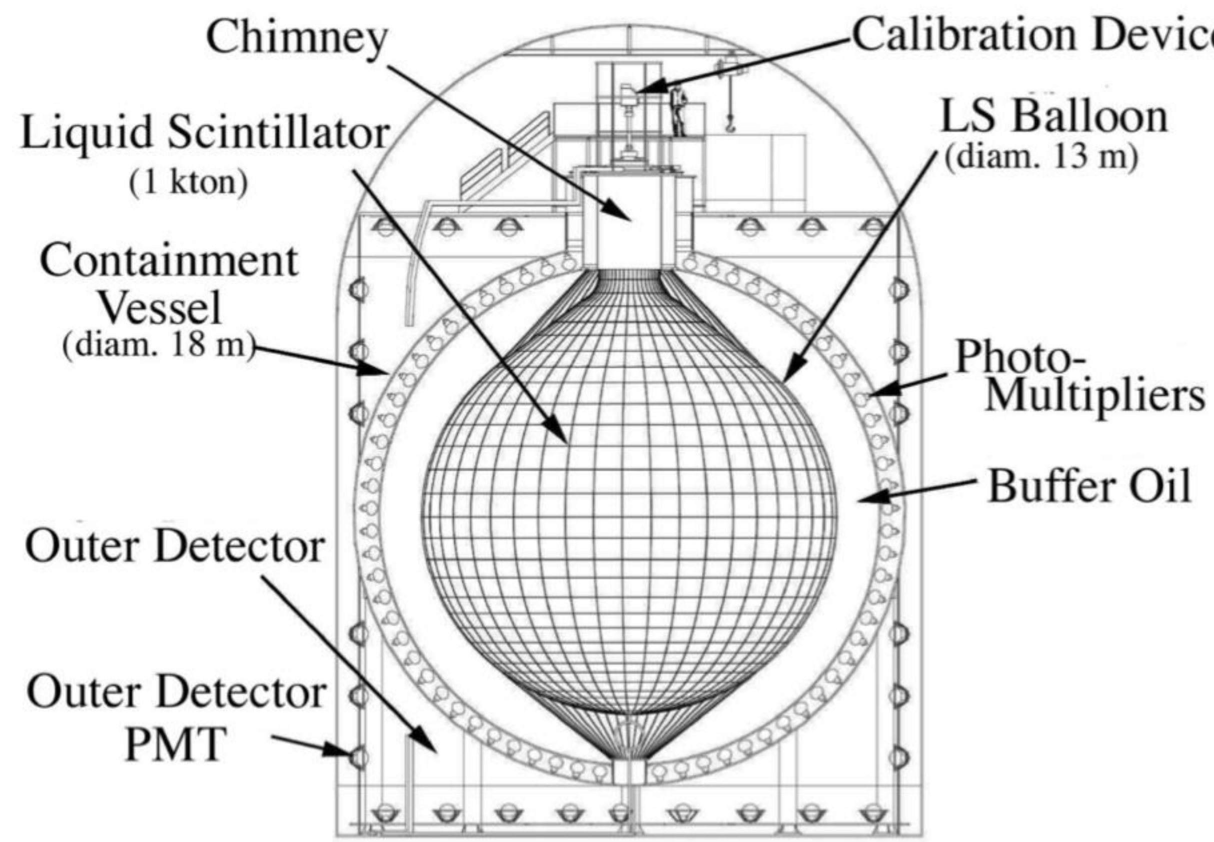
not yet observed (GZK neutrinos)

just observed!
announced July 12th 2018

flux is too low

not useful for oscillation searches!

KamLAND: search for “solar” oscillations



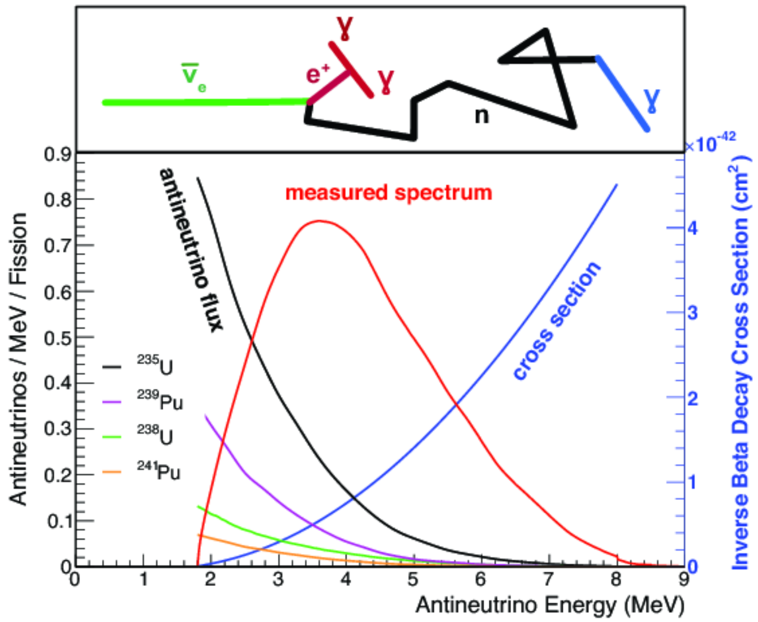
- 2700 m.w.e overburden
- 1kton liquid scintillator detector
- 1325, 17’ PMTs, 554, 20’ PMTs
- average $\bar{\nu}_e$ energy is 4 MeV
- baseline L~100 km

$$\cancel{\Delta m^2_{23}(eV^2)\frac{L(km)}{E(GeV)} \sim 2.5\cdot 10^{-3}\frac{100}{4\cdot 10^{-3}} \sim 50}$$

averaged out…

$$\boxed{\Delta m^2_{12}(eV^2)\frac{L(km)}{E(GeV)} \sim 7\cdot 10^{-5}\frac{100}{4\cdot 10^{-3}} = 1.75}$$

"1-2 (solar) oscillations" confirmed by KamLAND

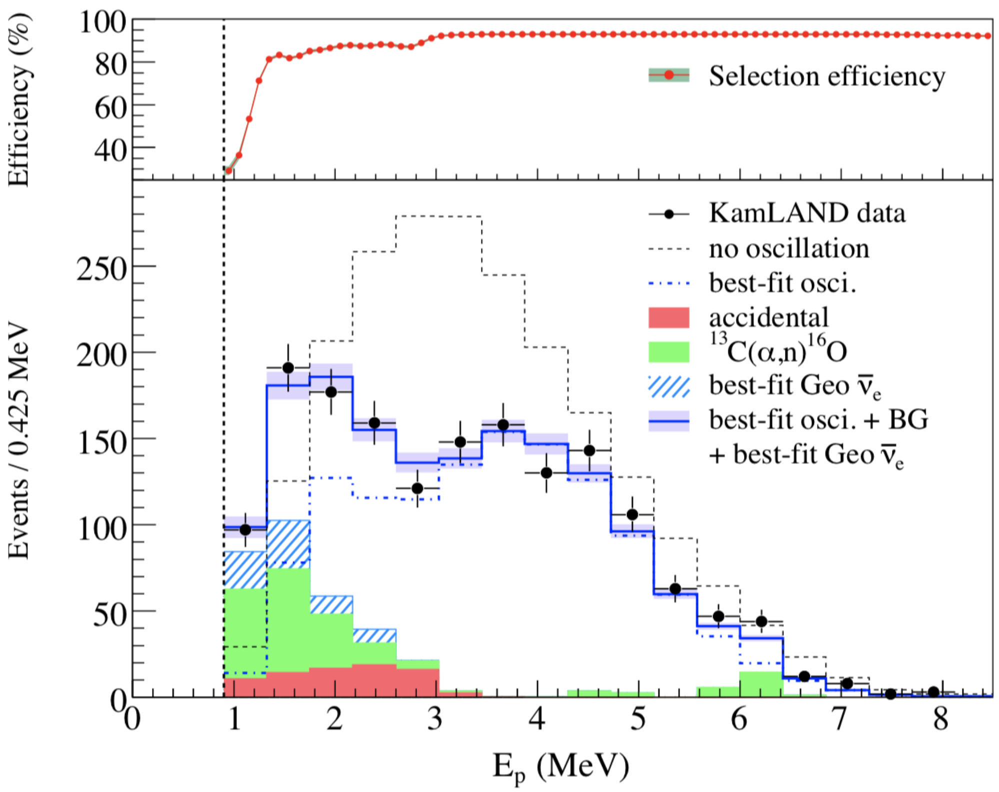


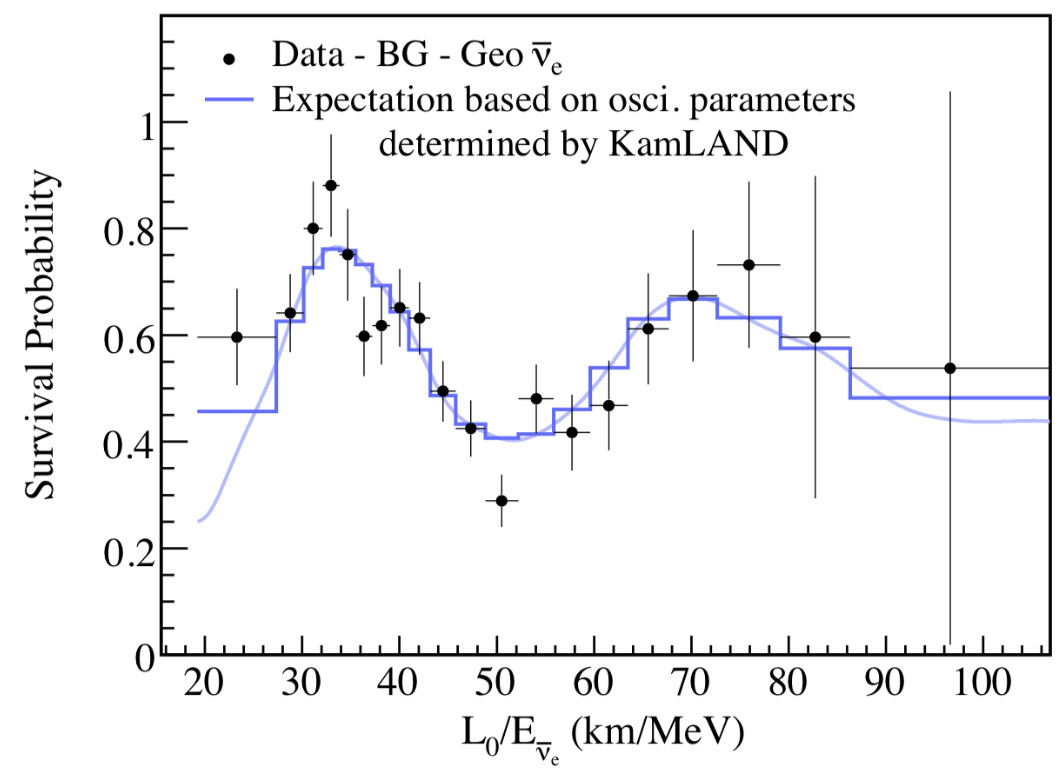
- Inverse beta decay on H (2.2MeV γ with a threshold of 1.8MeV)
- Two neutrino oscillation (1-2) approximation holds!

CPT

$$P^{2\nu}(\nu_e \to \nu_e) = P^{2\nu}(\bar{\nu}_e \to \bar{\nu}_e) \equiv P^{2\nu}_{ee}(\theta_{12}, \Delta m^2_{21})$$

$$= 1 - \frac{1}{2}\sin^2 2\theta_{12}\left(1 - \cos\frac{\Delta m^2_{21}}{2p}L\right) = 1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}}{4E}L\right)$$





Adiabatic conversion in the Sun

- When propagating **in matter, electron neutrinos get a phase for forward scattering with electrons.** This affects oscillations, because **matter is made of electrons**, and not of muons or taus
- Effectively, the presence of the electrons changes the neutrino propagation eigenstates
- This means that **in matter the mixing is different than in vacuum**: the effective matter mixing angle depends only on the electron density!
- This is the **Mikheyev-Smirnov-Wolfenstein (MSW) effect**

$$H = \frac{G_F}{\sqrt{2}} \int d^3x \ \overline{\nu_e} \gamma^\mu (1-\gamma_5) \nu_e \ \langle \bar{e} \gamma_\mu (1-\gamma_5) e \rangle$$

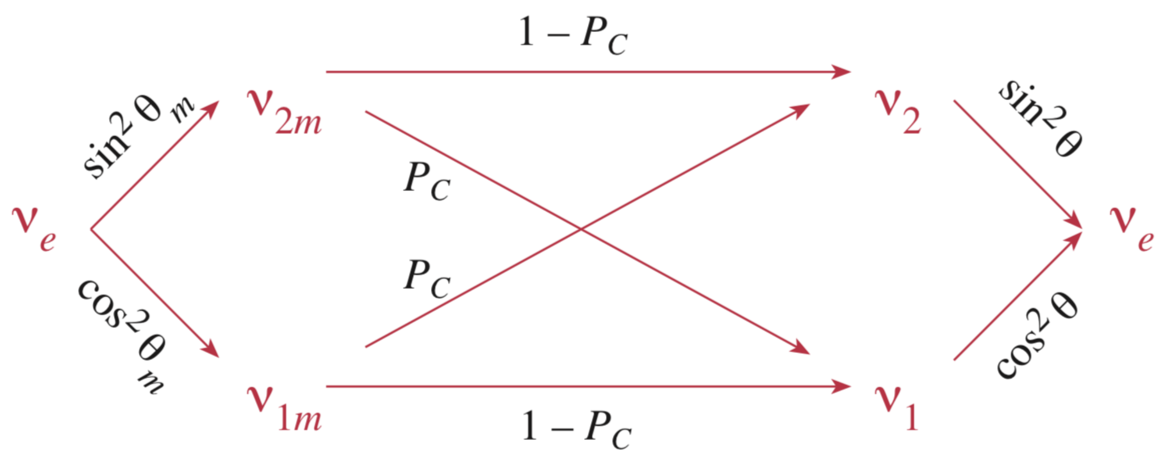
$$\nu_e = \cos\theta_{12}^m \ \nu_{1m} + \sin\theta_{12}^m \nu_{2m},$$
$$\nu_a = -\sin\theta_{12}^m \nu_{1m} + \cos\theta_{12}^m \nu_{2m},$$

Phase given by the matter effect

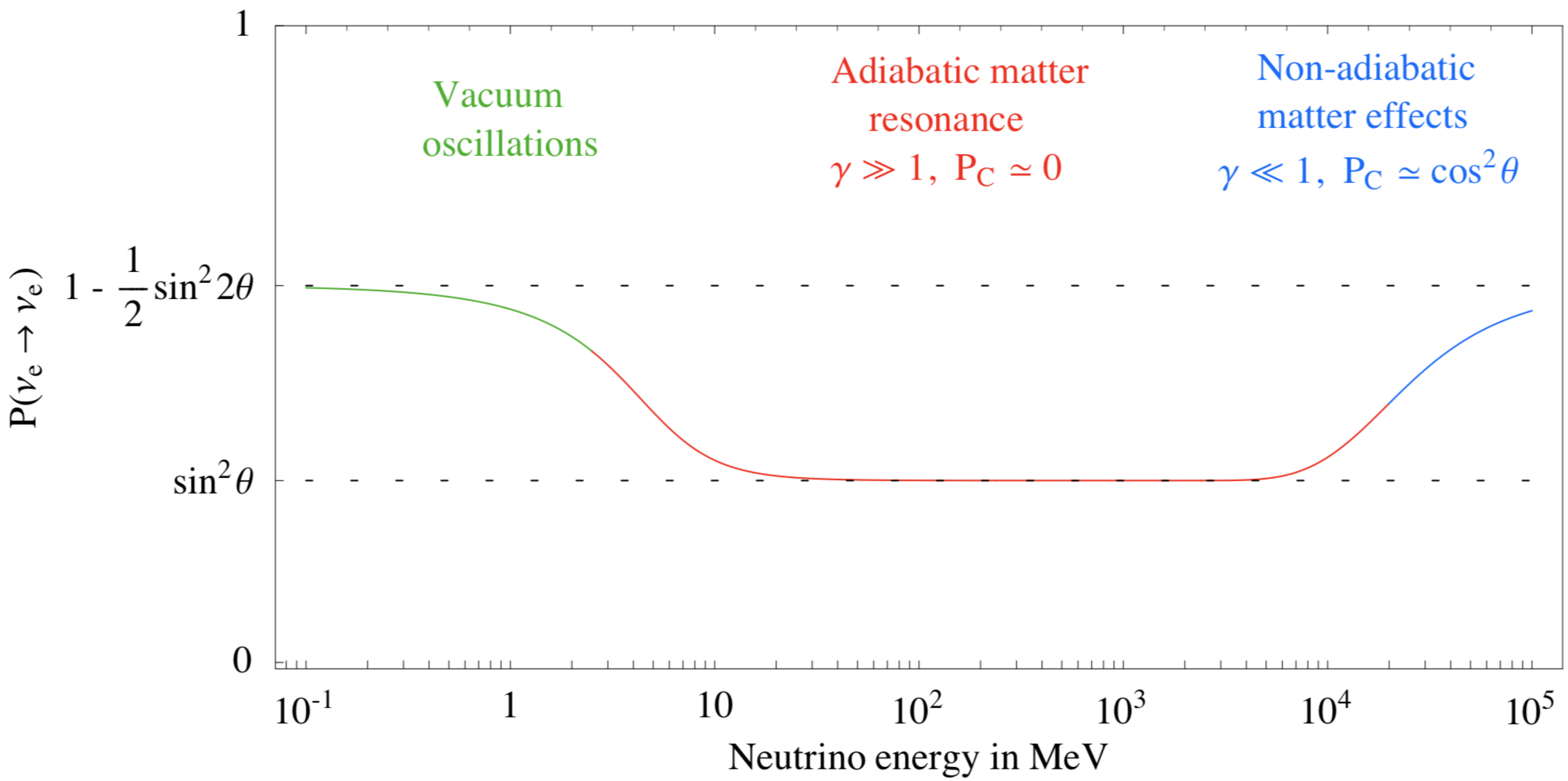
$$\varepsilon \equiv \frac{\sqrt{2} G_F n_e}{\Delta m^2/(2E_\nu)} \approx \begin{cases} \left(\frac{7.5\times 10^{-5}\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{5\ \mathrm{MeV}}\right)\left(\frac{\rho_e}{100\ \mathrm{mol/cm}^3}\right) & \text{“solar” MSW effect} \\ \left(\frac{2.4\times 10^{-3}\mathrm{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{5\ \mathrm{GeV}}\right)\left(\frac{\rho_e}{3\ \mathrm{mol/cm}^3}\right) & \text{not yet observed} \end{cases}$$

from F. Vissani

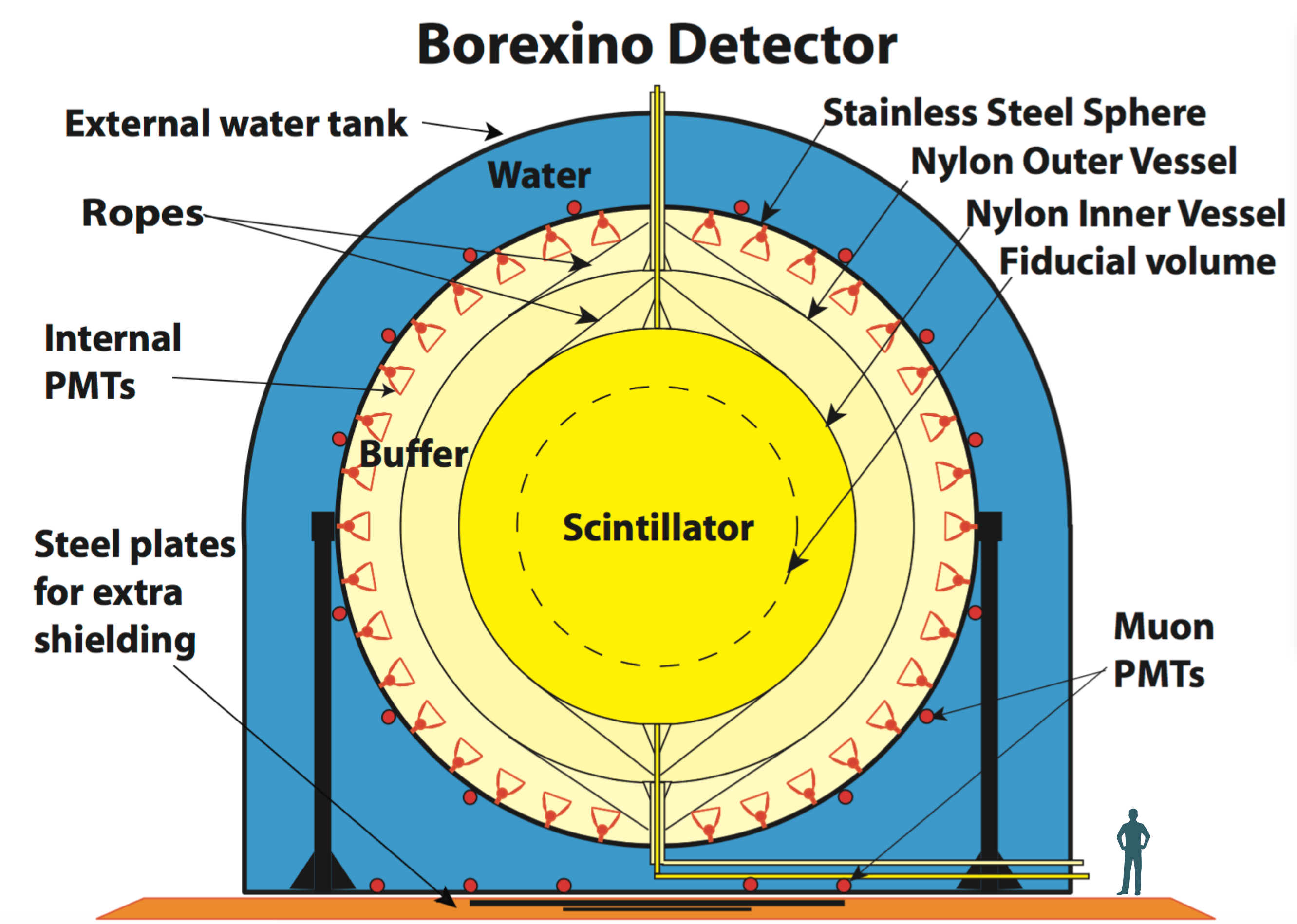
Solar neutrino propagation

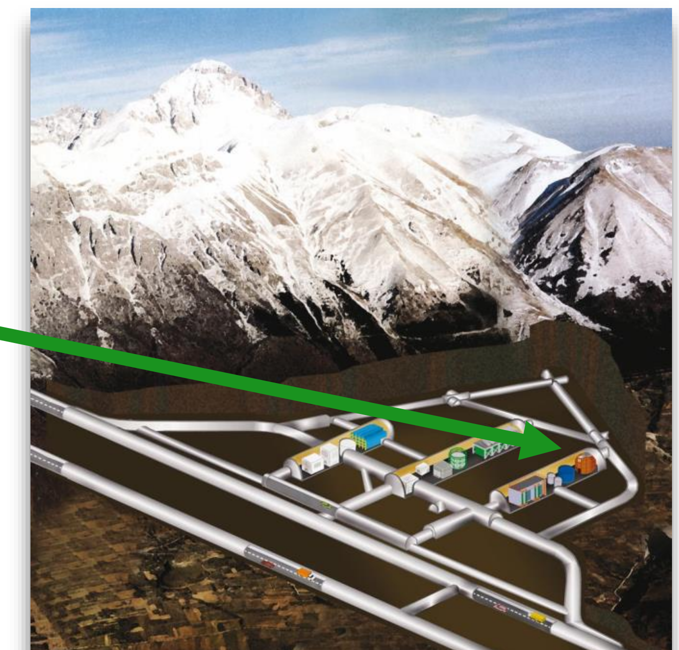


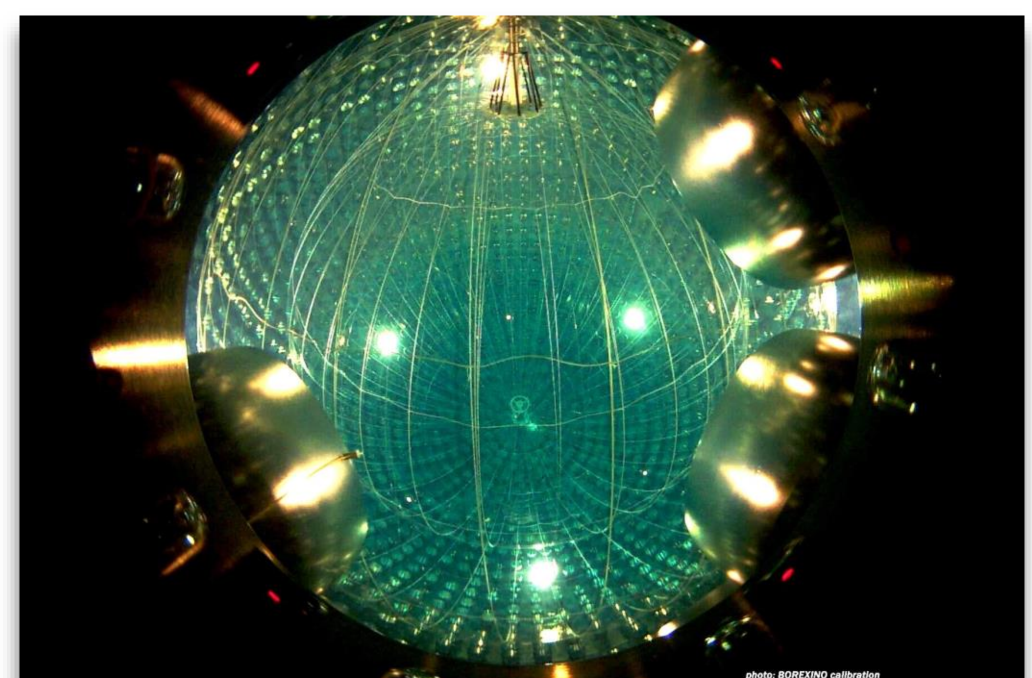
Vissani, Strumia,
https://arxiv.org/pdf/hep-ph/0606054.pdf



Borexino @ Laboratori Nazionali del Gran Sasso



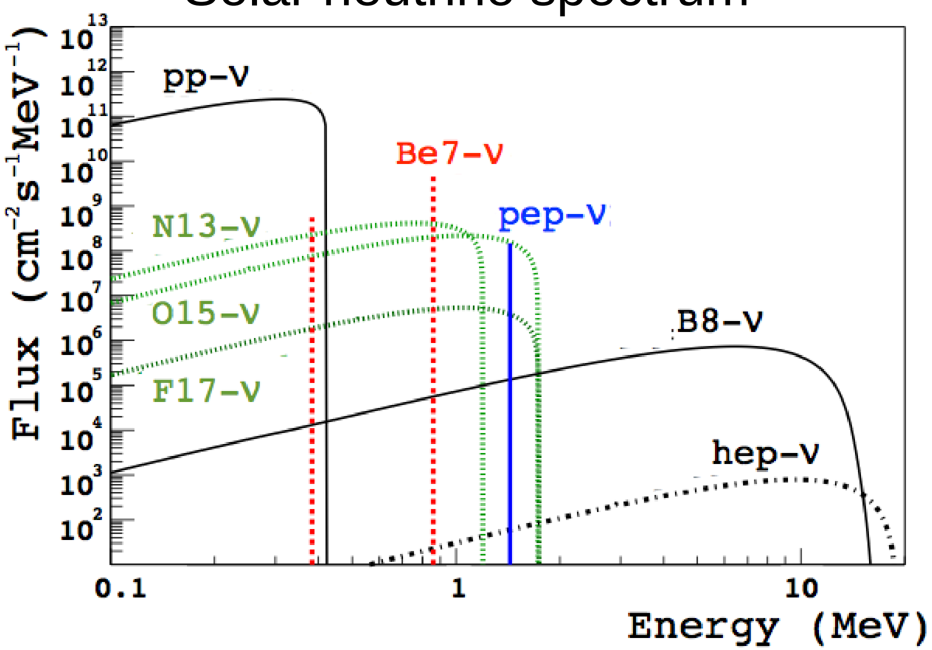


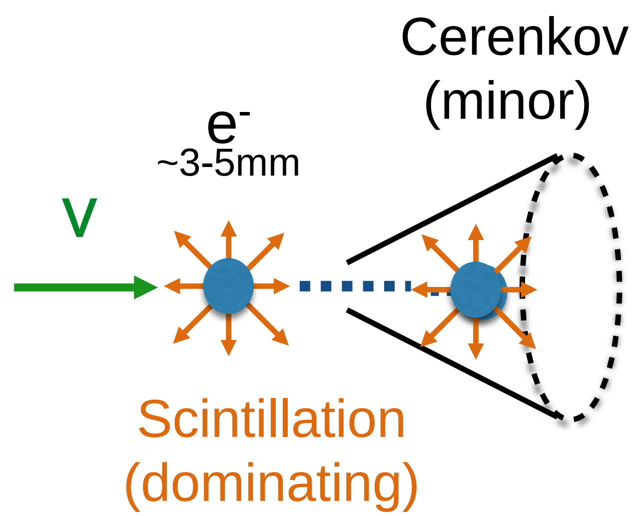


- 3800 m.w.e shielding against cosmic rays at LNGS
- active volume ~300 ton of liquid scintillator
- ~900 ton of ultra-pure buffer liquid
- 2212 PMTs detecting the scintillation light
- water Cherenkov veto equipped with 208 PMTs

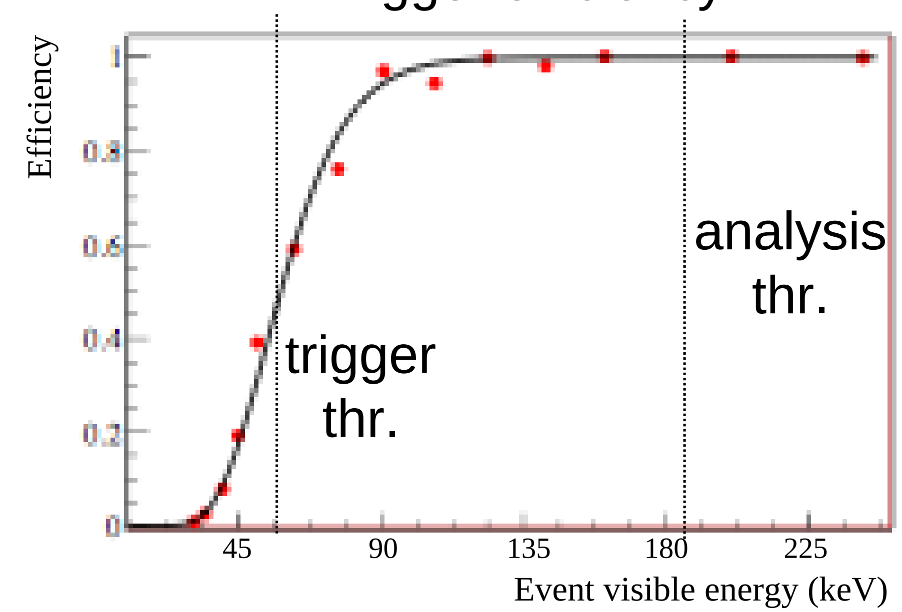
Borexino's strategy (PRD 89 112007 (2014))

Solar neutrino spectrum



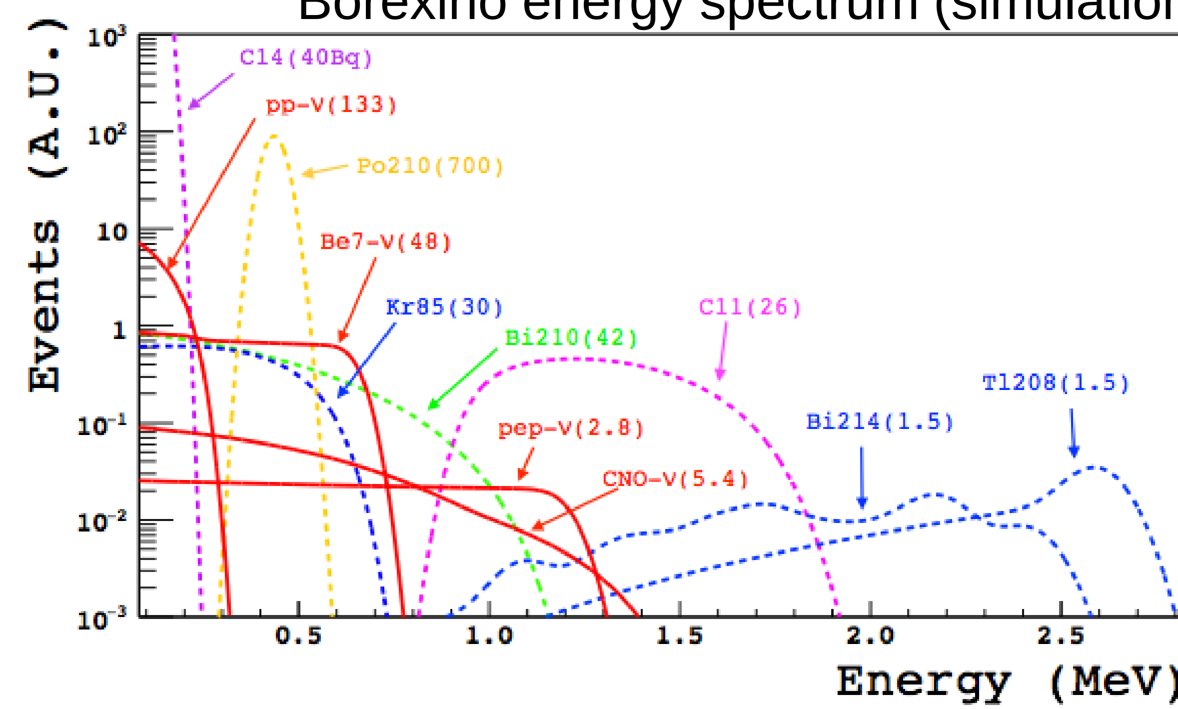


Trigger efficiency

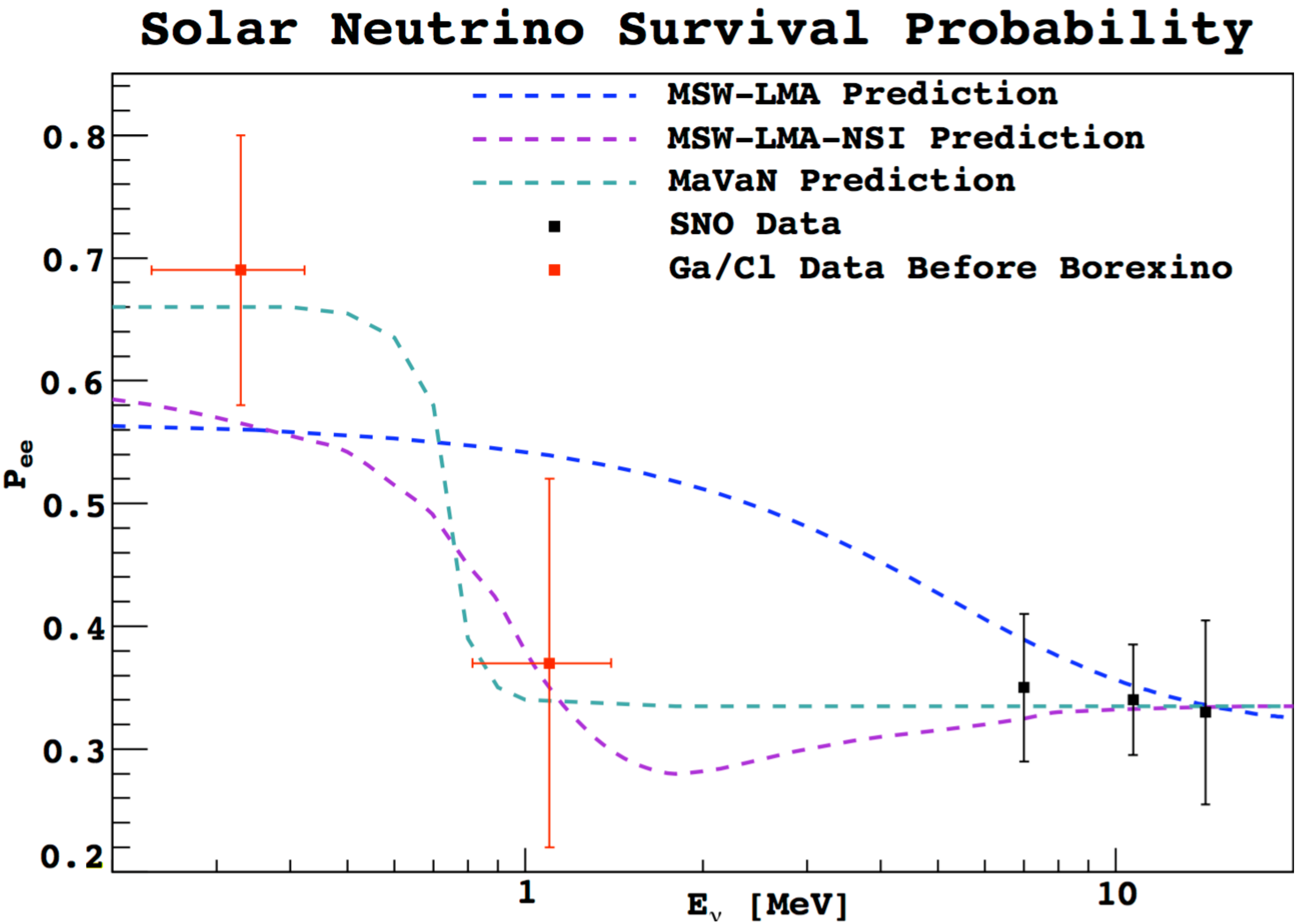


- Very low energy threshold (~100 keV) and good energy resolution ~ 5% @ 1MeV
- Pulse shape α/β, β+/β- but no directionality
- **Need of superb radio-purity** against β/γ backgrounds
- Strategy: spectral fit of event energy spectrum
- <u>Requirement: accurate understanding of detector's response</u>

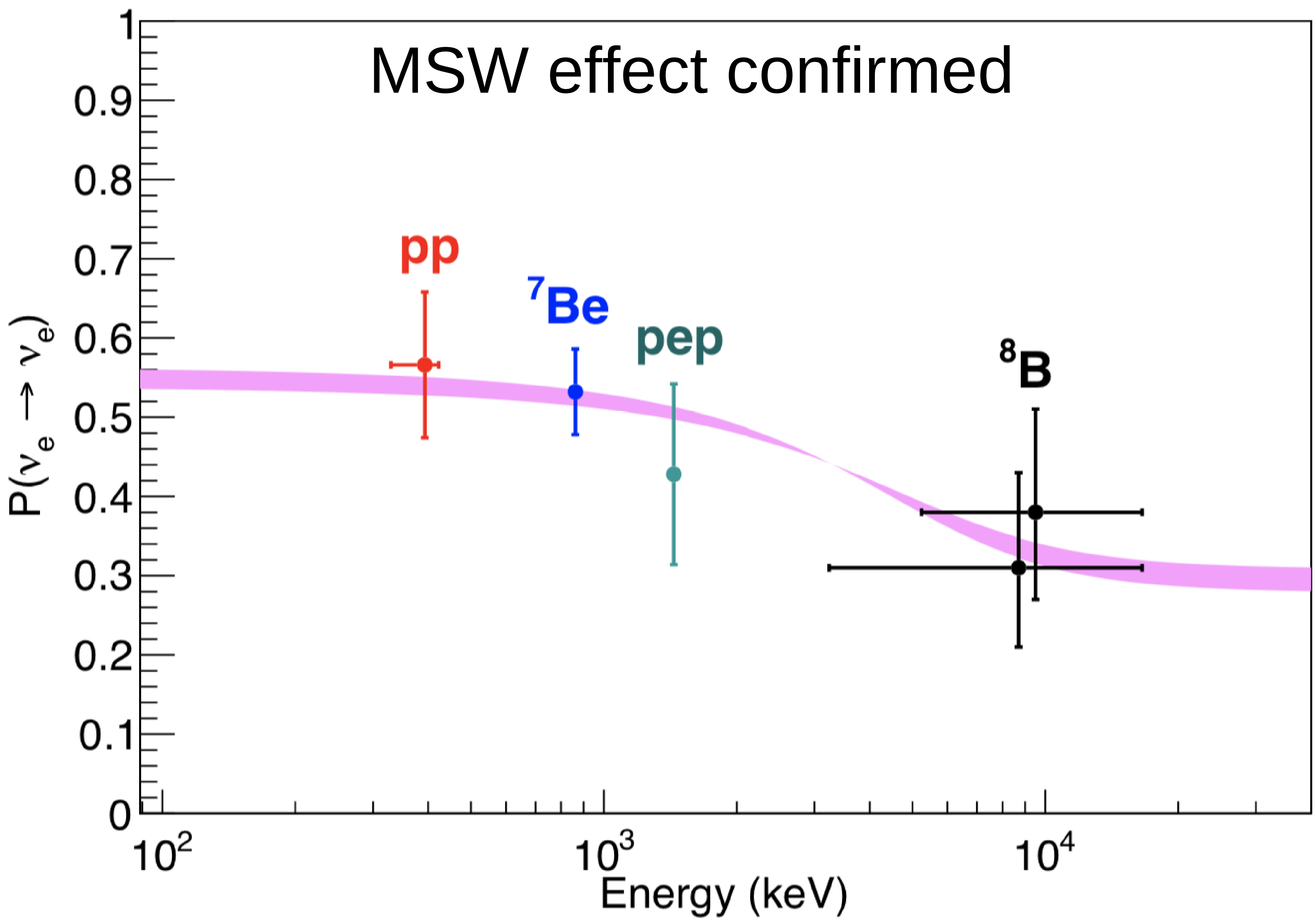
Borexino energy spectrum (simulation)



Before Borexino



Borexino results (arXiv:1707.09279)



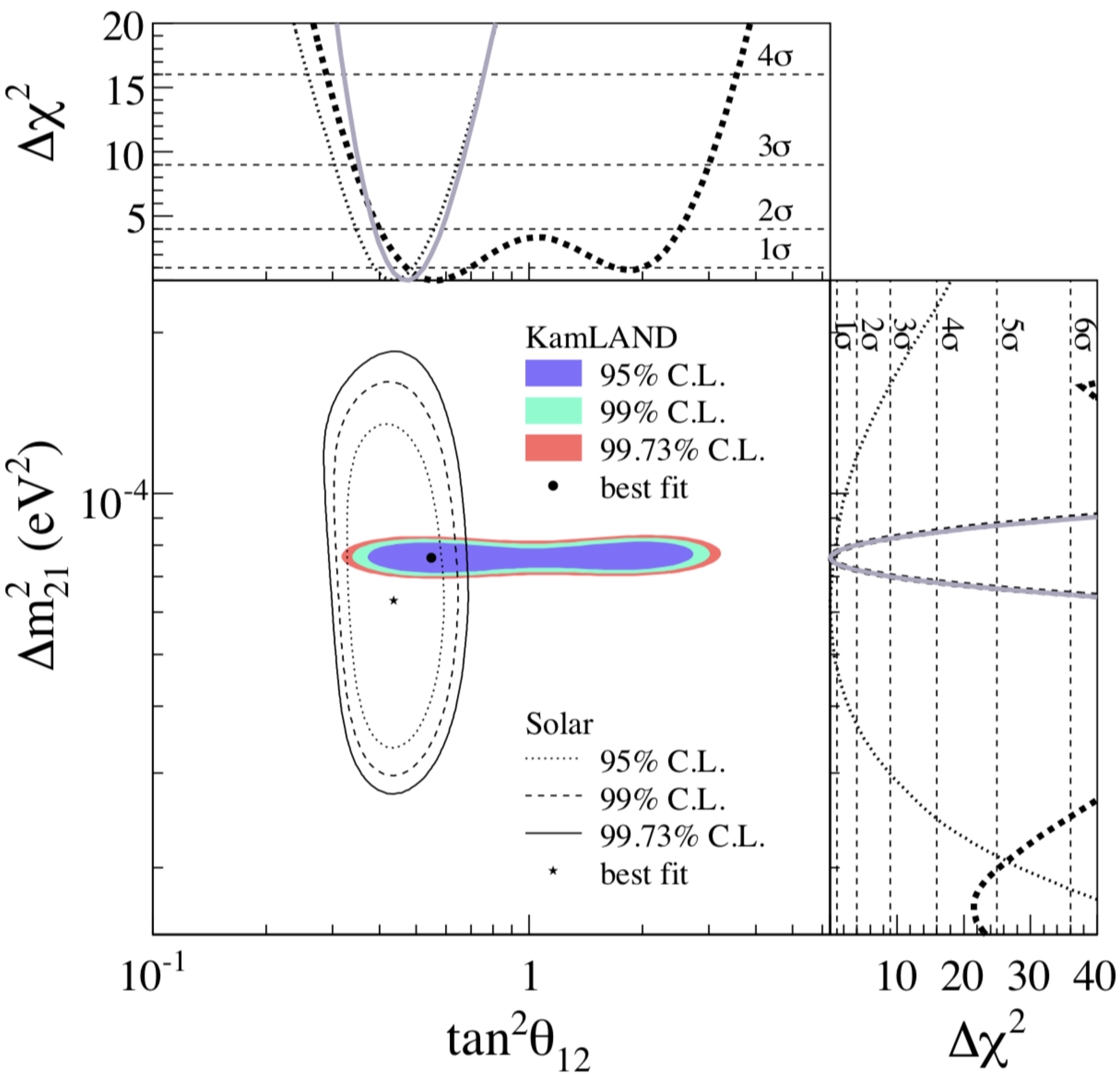
Super-K has also measured ^{8}B solar neutrinos with better precision

Summary on “solar” oscillations

- **“Disappearance”**
  - Borexino and Super-K confirm electron neutrino disappearance as predicted by the MSW effect
  - This was earlier observed by Ray Davis and the Gallium experiments
  - KamLAND has observed consistent electron anti-neutrino disappearance
- **“Appearance”**
  - SNO has observed that the total number of neutrinos from the Sun is fixed, and indirectly observed ν_μ and ν_τ appearance
  - Why not “direct” observation?

the picture looks consistent with neutrino mixing and oscillations!

KamLAND vs solar



There is a ~2σ “tension” between KamLAND and solar experiments

Is this a statistical fluctuation? Is it a systematics effect?

Is there new physics (NSI) happening in the matter?

A few more words on this tomorrow!